ASSESMENT OF POWER QUALITY OF PHOTOVOLTAIC GENERATIONS

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A Thesis report on

ASSESMENT OF POWER QUALITY OF PHOTOVOLTAIC GENERATIONS

in partial fulfilment of the requirements of the degree in

M Tech dual degree (Power, Control and Drives)

By

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May 2015

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CERTIFICATE

This is to certify that the thesis entitled **"Assessment of power quality of photovoltaic generations "**, submitted by **Biswbandhu Nayak (Roll No. 710EE2145)** in partial fulfilment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** & **Master of Technology** in **Power Control and Drives (Integrated Dual Degree)** during session 2014-2015 at National Institute of Technology, Rourkela.

The candidate has fulfilled all the prescribed requirements.

The Thesis is an authentic work, based on candidates' own work.

To my knowledge, the thesis is up to the standard required for the award of a Bachelor of Technology in Electrical Engineering & Master of Technology in Power Control and Drives (Integrated Dual Degree) degree.

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ACKNOWLEDGEMENTS

I wish to express my heartfelt gratitude to my supervisor Prof. P.K Ray, Assistant Professor, Department of Electrical Engineering, National Institute of Technology, Rourkela for his valuable support, guidance, time and inspiration throughout my project. I also appreciate the freedom provided by Prof. P.K Ray to explore new ideas in the field of my project. I am also grateful to Prof. S. K. Sarangi, Director, National Institute of Technology, Rourkela for providing me with outstanding facilities in the institute for my research.

I would also like to thank Prof. A. K. Panda, Head of Department, Department of Electrical Engineering, National Institute of Technology, Rourkela for providing facilities during my project work.

Finally, I want to thank my parents and the almighty god for their backing, without which this would not have been conceivable.

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Table of Contents

ABSTRACT

In the recent times distributed generations or renewable energies are very much needed for daily usage as the natural resources are on the verge of extinction. These renewable energy sources are a very good solution for the global energy problem. The usage of renewable energy, according to the statistics is around 17% all over the world, from which only 0.06% constitute of solar PV power. These statistics show that we are lagging behind from extracting the solar power. There are various factors that can be hold accountable for this viz. very costly equipment, lack of knowledge and even we do not have enough technology to harness the solar power.

Solar power, as most renewable energy sources, is not a steady power source. We only can utilize or store it during daytime. We try to find the maximum power point (MPP) of the PV array and then it is supplied to the grid. There are two different methods to track the MPP – Perturb and Observe (P&O) method and Maximum Power Point Tracking algorithm method (MPPT). In this project MPPT algorithm is used to track the MPP.

The MPPT algorithm uses the I_{PV} and V_{PV} of the PV array and gives the MPP and a $V_{DC,REF}$. This voltage is then passed on to the inverter and then further to the three-phase grid.

In this thesis the behaviour of the active and reactive power of the grid which is supplied by the PV array is investigated. The various currents such as inverter current, grid current and load currents are also investigated.

List of Figures

List of Tables

List of abbreviations

DG – Distributed Generations

PV – Photovoltaic

DS – Distributed Systems

PQ – Power Quality

DHES – Distributed Hybrid Energy Systems

DC – Direct Current

AC – Alternate Current

DER – Distributed Energy Resources

MPPT – Maximum Power Point Tracking

P&O – Perturb & Observe

IC – Incremental Conductance

A – Ampere

W – Wattage

V – Voltage

Chapter 1

1.1 Introduction

In the recent times distributed generations or renewable energies are very much needed for daily usage as the natural resources are on the verge of extinction. These renewable energy sources are a very good solution in the global energy problem. The energy generated by the photovoltaic systems constitutes a large part of the total amount of energy produced by renewable energy sources. Photo voltaic cells belong to the group of distributed generations. These cells produce power by utilizing the sunlight. There have been many research efforts to improve the efficiency of photovoltaic systems. These efforts were aimed at supplying the grid with active and reactive power. In periods when there is no sunlight, the inverter supplies the grid only with reactive power. Power quality analysis of these cells require the study of active and reactive powers and all the disturbances associated with them such as harmonics, sags etc. Investigation of the behaviour of a three phase grid-connected photovoltaic system to control active and reactive power have been carried out. MATLAB/Simulink has been used to carry out the simulations.

1.2 Literature review

For investigating the active and reactive powers of the PV array with a three-phase grid references of many available literature were taken. The references taken were from basic understanding of DG technologies and their benefits in our usual life. [6] This paper introduces a survey of the revolutionary approach of DGs. Surveying DG concept may include DG definitions, technologies, applications, sizes and locations. There are different types of DG:

- Traditional
- Non-traditional

Traditional include micro-turbine and non-traditional include electrochemical devices, storage devices, renewable devices. Micro-turbines operate using natural gas, propane, fuel oil. MT runs at less temperature and pressure and at faster speed. Then the advancements in DG technologies was studied [5] The main and important distributed generation technologies are in wind power generation technology, solar photovoltaic technology and in fuel cell technology. In the wind power sector new wind turbines are being produced which increases the efficiency of the plant and in PV sector scientists are working on lowering the cost of the PV arrays and to increase their efficiency. The main research objective in the fuel cell production is reduction of costs and improvement in the performance in the aspects of production, material, systems and applications. The impact of DG over the power system transients and voltage stability was studies. The different positive and negative impacts were observed. The various problems associated in DG technologies due to the phenomenon such as malfunctions, failure of electrical equipment, instabilities and weather related issues were studied. [4]

1.3 Motivation

- The renewable resources or the distributed generations can cope with the global energy crisis.
- Photovoltaic systems have a major contributions in the total power generation from the distributed generation technologies.
- The photovoltaic system can be installed almost everywhere as it has sun as its source.
- The power quality of these generations need to be improved.

1.4 Objective

- To determine the disturbances in the power quality of the photovoltaic systems.
- To find a way to improve power quality of the photovoltaic systems connected to a grid.
- To improve the output of the photovoltaic generations during different weather conditions.

1.5 Thesis layout

- Chapter 1: Introduction, motivation and objective.
- Chapter 2: Distributed Generations
- Chapter 3: Photovoltaic Array
- Chapter 4: MPPT algorithm
- Chapter 5: Three phase grid connected PV array
- Chapter 6: Results and Discussions

Chapter 2

Distributed Generations

2.1 Introduction

The recent times have brought this revelation to us that the mainstream energy resources are on the verge of extinction. If we do not find alternate resources to provide with energy, then our future generations will suffer for it. The best way to curb this energy crisis problem is to use distributed generations. The usage of DG also comes with some challenges such as low power quality, voltage sags, harmonic disturbances, voltage rise effects and stability of power supply [14]. These problems needed to be minimized for the better usage of DG.

2.2 Definition of DG

The definition of DG not similar all around the world [6]. Different countries define DG according to its purpose, rating, technology used and many other factors. Distributed generation technologies are of many two types which are discussed in the section below.

The purpose of DG is to provide a certain number of consumers with clean energy using renewable energy resources. These DG systems mostly are used with a three phase grid connected to them but they can also be used as stand-alone devices for power supply. One important factor of using DG is their location, which should be near to the consumers as DG does not produce a huge amount of power. This would help minimize the in-line losses during the transportation of power. We can even use batteries and other energy storing devices to improve the efficiency of the DG in use. Based on the ratings of the DG they are divided as follows:-

Table 2.1 DG based on power ratings

Type of DG	**Power Rating**
Micro	1 W – 5 KW
Small	5 KW – 5 MW
Medium	5 MW – 50 MW
Large	50 MW – 300 MW

The power delivery area or the number of consumers for a particular DG system should not be more as DGs do not provide enough power to feed a large number of consumers [11]. The modes of operation of DG are of two types - (i) the power can directly be fed to the consumers, (ii) or the power can be stored using storage device and distributed later in the time of need. The main objective of DG technologies are that they can be used as supportive power generation devices and they can assist the regular power generation methods such as hydro power plants or the thermal power plants. New technologies are always being researched to improve the efficiency of the power quality of DG systems. These technologies do not have a negative impact over the environment as DG produces clean energy which is environmental friendly.

2.3 Types of DG

The types of DG depends upon the technologies, application, size and location of the system [11]. There are two different types of DG:-

- Traditional
- Non-traditional

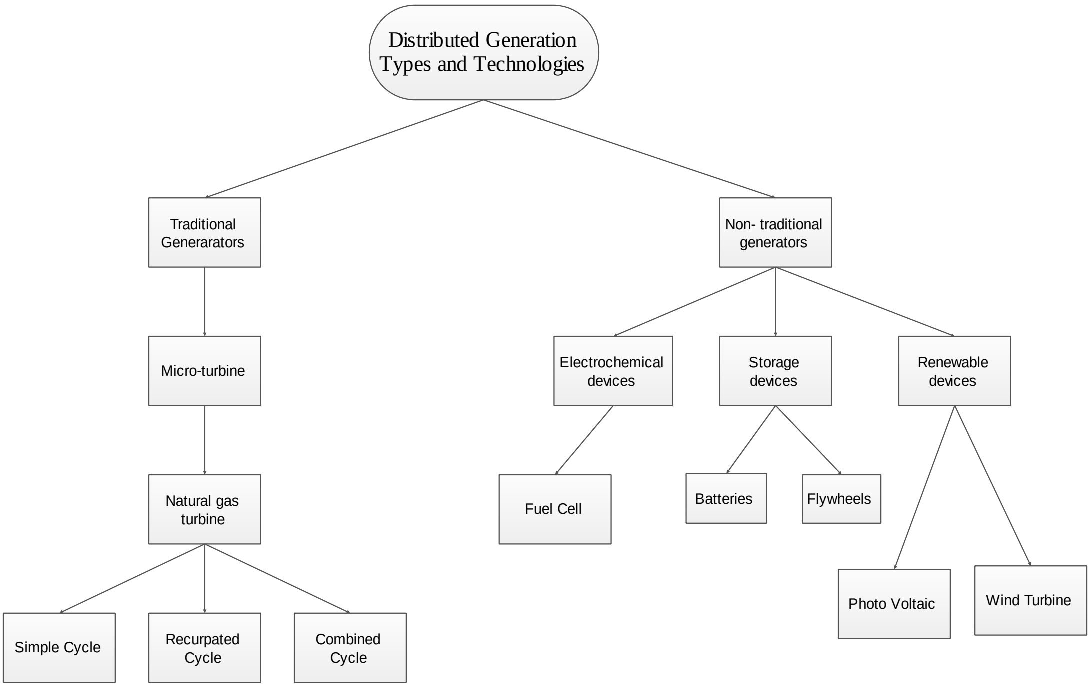

Fig 2.1 Types of DG

Traditional include micro-turbine and non- traditional include electrochemical devices, storage device and renewable energy systems. Micro turbines operate using natural gas, propane, fuel oil etc. Micro-turbine runs at less temperature and pressure and at faster speed. Advantages of micro-turbine are:-

- It takes less space.
- Micro-turbines are very efficient energy generation devices.
- The installation of micro-turbines are relatively easy.
- The power supplied is of low cost and

The types of micro-turbines are BAS and combustion type where gas type can be further classified into simple cycle gas, recuperated gas and combined cycle gas type micro-turbine.

Fuel cell are another type of DG technology which provides energy through electrochemical process like a battery. There is no need to charge the fuel cell. The fuel cell operates at various temperature and uses various kinds of fuel. The fuel cell uses the cathode and anode concept where two oxidant electrodes are used as cathode and anode.

Advantages of Fuel cells:-

- Fuel cells provide 60% efficiency.
- It does not include any movable parts and hence energy losses are minimum.
- Combustion does not takes place in a fuel cell.

The non-traditional DG types includes the renewable resources of power generation:-

(i)Wind energy systems

In wind energy systems a wind turbine is used. The wind turbines are located in places with high wind speed. According to the wind speed the turbine rotates and a generator attached to the turbine produces electricity.

(ii)Photo- Voltaic cells

The photo-voltaic cells use the solar radiation to produce electricity. These PV cells are made up of silicon and other semi-conductor devices which absorb power from the sun and convert it to electrical energy. The circuit diagram of a photo-voltaic cell is shown in Fig 2.2. The solar cells are used in series or parallel combination to constitute a photo-voltaic array. These arrays then convert energy during the day and may also be used to store energy in batteries. Then this stored energy can be used during the night.

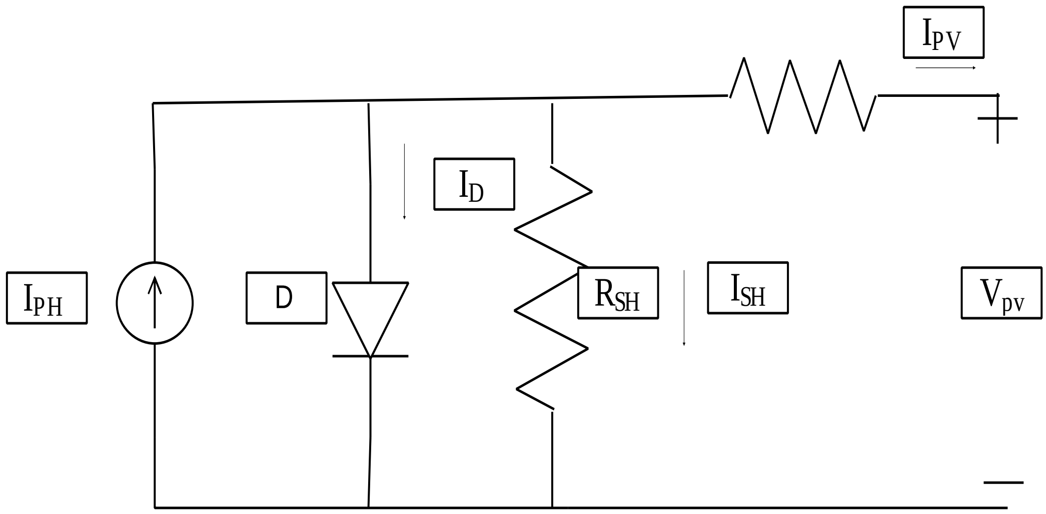

Fig 2.2 Photovoltaic cell

2.4 Advances in DG

The main and important distributed generation technology are in wind power generation technology, solar photovoltaic (PV) technology and fuel cell technology. In the wind power sector new efficient wind turbines are being implemented which increases the efficiency of the wind farm and in PV sector scientists are working on lowering the cost of the PV arrays and to increase their efficiency. At present the biggest hurdle of photovoltaic generation is the high price of solar cells, which accounts for over 60% the price of the whole solar photovoltaic generation system, so the solar cells research such features as cheap price, high efficiency, high reliability, high stability, long lifetime has become the world's focus. In addition, the focus of photovoltaic generation is shifted gradually to components research and system development for grid-connected photovoltaic generation system, such as grid-connected inverter, BIPV, large-scale grid-connected photovoltaic station and the automatic tracking systems of photovoltaic arrays. Research is underway in the reduction of voltage sags, harmonics and other anomalies associated in the DG sector. The main research objective in the fuel cell production is the reduction of costs and the improvement in the aspect of production, material, system and applications.

Micro grids

Micro grid consists of DG, load, DS, power conversion equipment and control system. DG in micro-grid can be connected to utility grid directly by static switches. The control problem associated with the micro-grid are external characteristics, time constants and composition of micro-sources. Load for micro-grids is to be carefully classified or else complexity may arise. Low power supply and PQ load are at the bottom position while high power supply and power quality load are at top position of the pyramid. Micro-grids can sustain a certain amount of consumers even if they are disconnected from the larger grids unlike the DG systems.

Recently new hybrid generation systems are being used along with the micro-grids to provide power. This is known as DHES. There are different type of DHES:-

- Wind turbine and battery with an AC grid connected to it and it satisfies an AC load.
- PV arrays and a battery satisfying a DC load.
- Fuel cell with hydrogen tanks supplying DC power.

Component modelling in DHES is similar to the micro-grid. The control problems associated with DHES are micro-sources which are flexible and controllable.

New smart micro-grid technology has also been implemented. In a smart micro-grid the wind energy system, PV arrays and micro-turbines are connected to a single control centre which supplies the power to different consumers. Storage devices are also used as a supply to the control centre. The components associated with smart micro-grid are:-

- Power supply from the sources viz. from wind farms, PV arrays, micro-turbines and the storage devices.

- The different types of demands which includes sensitive, adjustable and sheddable demands. The management centre meets each demand according to the supply.
- The environmental factors such as low wind speed, rains also come into consideration of the efficiency of the smart grid.

These micro-grids are used because of the low amount of energy produced by the DERs. The major factors that contributes to the DG evolution are [12]:-

- DG technologies are being developed and scientists are researching on to increase the power quality of the generated power.
- New transmission lines need to constructed, so that the line losses while the transportation of power is less.
- As the customers demand for clean and un-hindered power supply is increasing. This also has helped in the advancement of DG.
- The electricity market has undergone liberation.
- The concerns about the climate of earth due to the usage of mainstream power generation methods also has helped the leap in DG research.

2.5 Benefits and problems related to DG

The benefits of DG are:-

- The application of DG in power system sector improves the reliability of the services, as they can be turned on when regular services are off.
- The usage of DG reduces the use of fossil fuel consumption, hence decreasing the emission of greenhouse gases and this reduces the pollution.
- The DG systems use wasted heat of the systems and hence increasing the efficiency of machines.
- They bypass the congestion in existing transmission grids.

The problems related to DG are:-

- DG can produce inversion in the power flow.
- The voltage control of DG is quite difficult as it is always fluctuating.
- The management of reactive power in DG is quite difficult.
- DG flow can reduce the effectiveness of the protection equipment.

Summary

The future of our civilization is in the hands of DG and for the advancement of DG the fields of active distribution networks, micro grids, virtual utilities, advanced power electronics and resource techniques needed to be improved.

Chapter 3

Photo-voltaic array

3.1 Introduction

A photovoltaic system basically uses one or more solar modules or panels in series or parallel connection according to the desire of the user to convert solar energy to electrical energy. The components required for a solar PV array are solar panel, electrical connections and mostly MPPT algorithms are used to find the maximum power point of the produced solar power. Sometimes storage devices are used to store the generated energy so that they can be used when there is no sun light.

3.2 Photovoltaic Cell

The photovoltaic cell is the building unit of a photovoltaic array. These cells are made up from semiconductor devices such as germanium, silicon etc. These semiconductor devices are used as very thin wafers who work on the principle of potential difference due to the presence of holes and electrons. Due to the potential difference across the wafer, voltage is produced. Electrons attain energy when subjected to solar radiation and are free to move around. If we connect an electrical circuit with the wafer, we can harness electricity from the wafers. The electricity is produced due to the movement of electrons causing the flow of current.

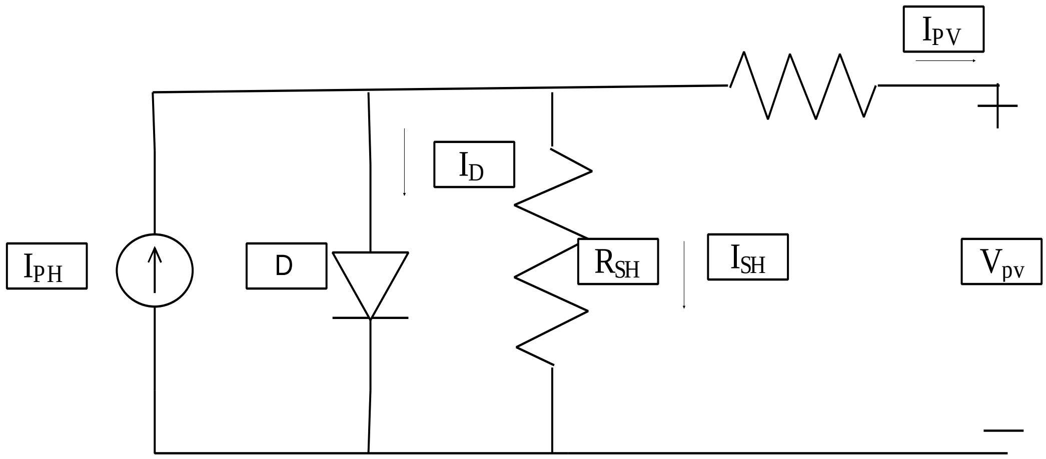

Fig 3.1 Circuit Diagram of PV cell

3.3 Photovoltaic Module

The voltage produced by each cell is very low, around 0.5-0.7 V. So, a large number of cells are connected either in series or in parallel to attain a much better voltage. Sometimes diodes are also used in the cells to prevent the reverse current. This mostly happens during the partial shading period. The solar panels needed to be set up at specific places so that they can have the maximum amount of irradiance during the day.

3.4 Photovoltaic Array

The power produced by one PV module is sometimes not enough of to facilitate power supply to certain consumers. So, we combine many modules to form a PV array, which produces enough power to meet the needs of customers. These PV arrays ensure the reliability of the power supply. Recently these PV arrays are being used in micro-grid concept with both wind turbines and fuel cells to provide electricity. As the PV arrays produce DC, we need to change them to AC for the day-to-day usage. So mostly they are combined with DC-DC boost converters to enhance the power and then with inverters to transform DC to AC. The modules are also connected in series and parallel as per the specifications of the user. [1]

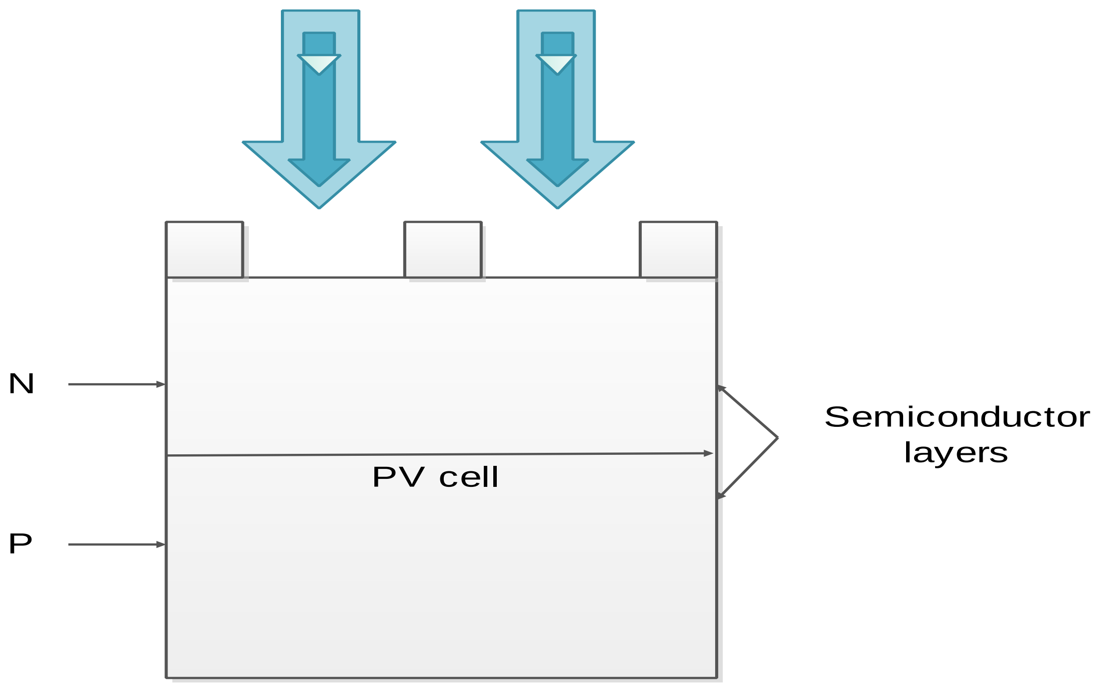

Fig 3.2 A PV cell

The photovoltaic cell's output voltage is due a function of the photocurrent. This photocurrent is produced due to the irradiation level of the sun light.

$$V_c = \frac{AKTc}{e} \text{Ln} \left(\frac{Iph+Io+Ic}{Io}\right) - R_s I_s$$

The symbols used are

V_c: cell output voltage, V.

T_c: reference cell operating temperature (20 °C).

R_s: series resistance of cell (0.001 Ω).

I_{ph}: photocurrent, function of irradiation level and junction temperature (5 A).

I_0: reverse saturation current of the diode ($2*10_{-4}$ A).

I_c: cell output current, A.

k: Boltzmann constant (1.38 × 10-23 J/K).

e: electron charge (1.602×10^{-19} C)

3.5 Conclusion

The photovoltaic arrays are the latest face of the DG technologies. These arrays are needed to be made cheaper so that we can use the solar power for our daily usage. The use of PV arrays prohibit the pollution and controls the use of fossil fuels.

Chapter 4

MPPT algorithm

4.1 MPPT algorithms

The MPPT algorithms are used to track the maximum power point of the DG technologies. The MPPT algorithms are used in PV arrays because the power supplied by the arrays is not always constant and is fluctuating in nature. For this we need to find the maximum power point and provide it to the inverters which then convert it to AC and supply to the grid. There are two types of MPPT algorithms:-

- Perturb & Observe method
- Incremental Conductance method

4.2 Perturb & Observe method

In this method a slight disturbance is created in the system. This disturbance created tends to alter the power of the PV modules. If the modification or disturbance created increases the power, then it travels towards a point where the power is maximum. This point is called the maximum power point. The operations are kept at hold at this point and power is being supplied to the further equipment.

The P&O method is the basic power point tracking method. This gives better results and is very widely used. This algorithm is elementary, hence having only one loop.

The restrictions of P&O method is that sometimes if the weather changes and the irradiation is altered, the power tends to decrease and the maximum power point could not be achieved.

4.3 Incremental Conductance Method

Incremental conductance method uses a voltage and a current sensor. These sensors are connected to the output voltage and current of PV array respectively. At MPP slope of the PV curve is always zero.

$$\frac{\mathbf{dP}}{\mathbf{dV}} \text{ Of maximum power point } = \frac{\mathbf{d(VI)}}{\mathbf{dV}}$$

$$\mathbf{0 = I + V\frac{dI}{dV}} \text{ of maximum power point}$$

$$\frac{\mathbf{dI}}{\mathbf{dV}} \text{ Of maximum power point } = \frac{\mathbf{-I}}{\mathbf{V}}$$

The above are the formulae used in an incremental conductance algorithm. We can see in the formulae that both current and voltage of the arrays are being used, along with the irradiation of the sun light. P is the conductance of the PV array and when the instantaneous conductance equals the conductance of the PV array, then only the MPP is reached. [1]

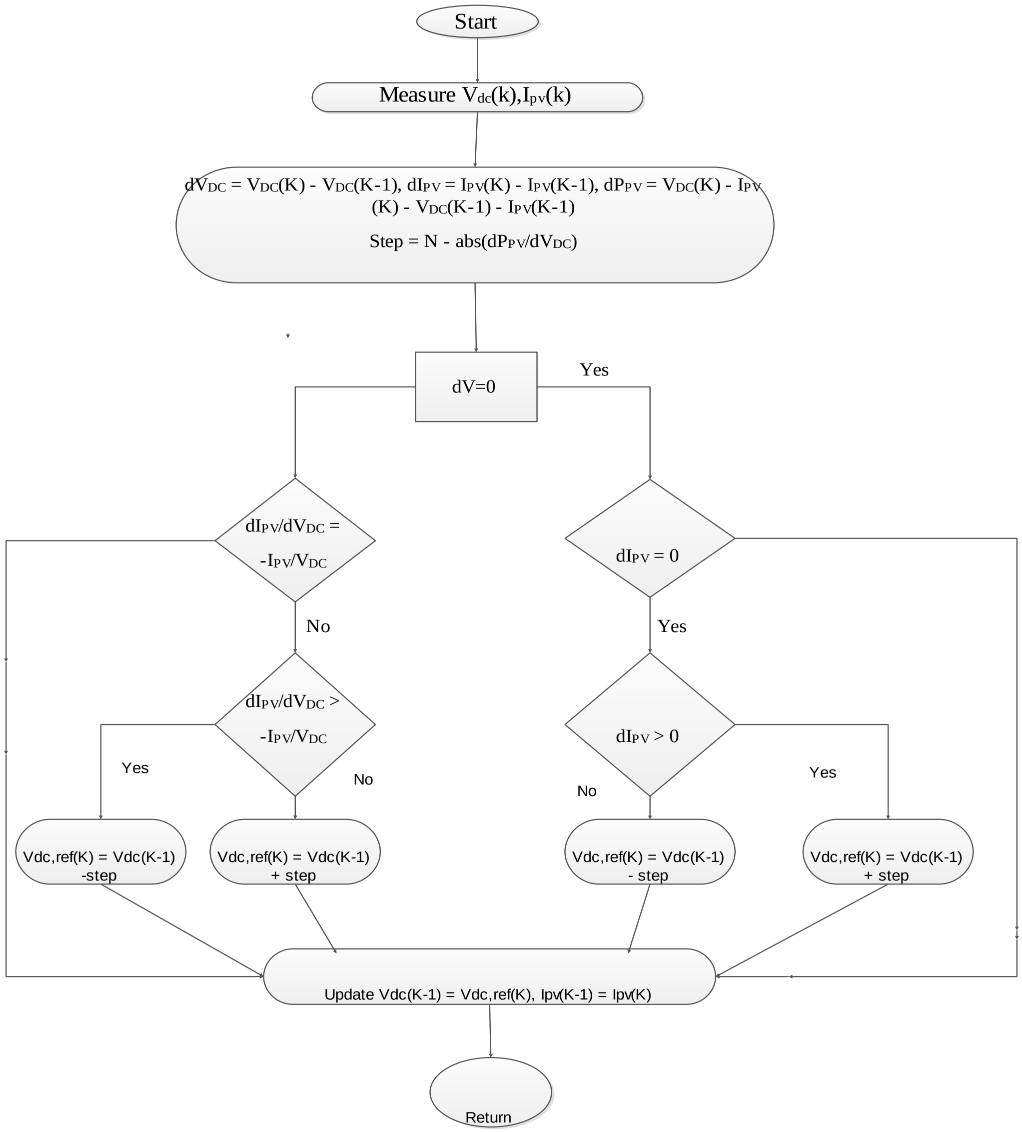

Fig 4.1 Incremental Conductance method algorithm

The above is the flow chart of the incremental conductance algorithm. This as we can see is a one loop algorithm. The problems associated with IC method is that it is very costly and difficult to install.

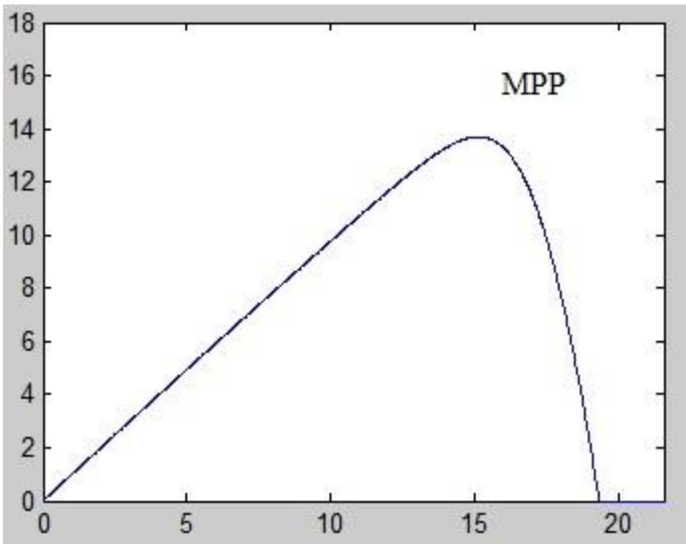

Fig. 4.2 MPP of a PV curve

The above figure shows the MPP of a PV curve of a photovoltaic array. As the instantaneous conductance comes closer to the conductance value the MPP rises to the top most point. When the MPP is reached, the operation are held for some moment as the power is connected to further equipment.

4.4 Conclusion

The MPPT algorithms both P&O and IC methods are commonly used to track the MPP of different DG technologies. These help in improving the power quality of the DG technologies. The drawbacks of these methods are their cost and if weather is not supportive then MPP cannot be located.

Chapter 5

Three phase grid connected PV array

5.1 Investigation of the behaviour of a three phase grid-connected photovoltaic system to control active and reactive power.

In this system a photovoltaic array is taken along with a three phase grid to investigate and observe the behaviour of the active and reactive power provided by the photovoltaic array. The system as shown in Fig 5.1 comprises of a photovoltaic array, an inverter, a three phase grid and loads. The photovoltaic array is comprised of many photovoltaic cells which when subjected to sun's radiation develops potential difference and provides voltage to the inverter.

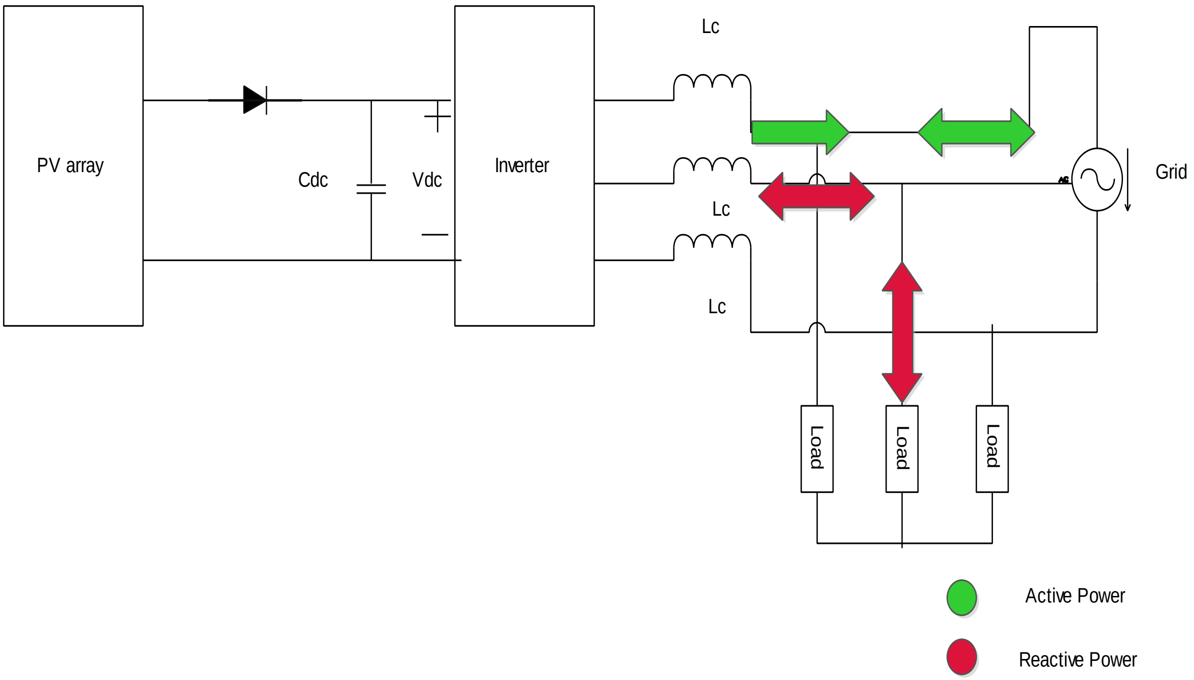

Fig 5.1 Grid connected photovoltaic system

The PV array provides the MPPT algorithm with I_{pv} (Photovoltaic current) and V_{pv} (photovoltaic voltage). Then the algorithm gives the MPP and a $V_{DC,REF}$ is produced. It is then passed through a selector with a constant value. The constant value is given because if there is less solar radiation and the $V_{DC,REF}$ is low then it can take its place and the grid can get uninterrupted power supply. The active and reactive power are calculated as shown in the figure. With the help of PWM hysteresis band gating pulse are given to the inverter which then supplies power to the grid.

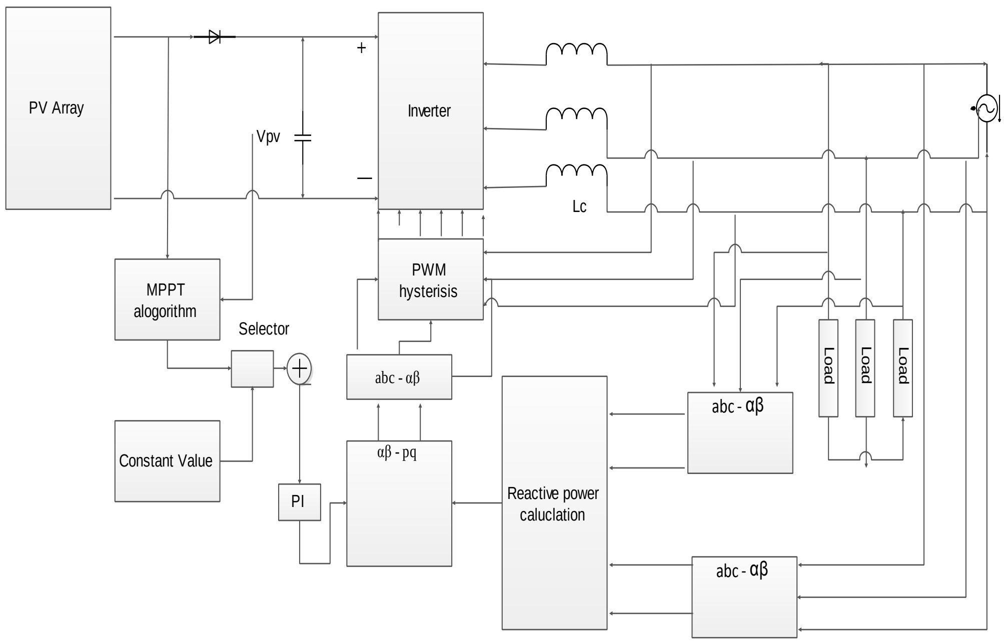

Fig 5.2 Control scheme proposed

Reactive Power Control

As the conventional methods suggests, d-q synchronously rotating frame is required for the calculation of reactive power. In three phase circuits the current and voltages are transformed into synchronous rotating frame according to the following equation:-

$$I_{L,dq} = K(\theta)I_{L,abc}$$

$$K(\theta) = \text{Transformation matrix} = 2/3 * \begin{bmatrix} -\sin\theta & -\sin(\theta - \frac{2\Pi}{3}) & -\sin(\theta + \frac{2\Pi}{3}) \\ \cos\theta & \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta + \frac{2\Pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

Active Power Control

The MPPT algorithm provides the MPP which provides the maximum power of the PV array. There are some switching effects in the inverter which induces losses in the circuit. The equation that shows the connection between active power of the inverter and with photvoltaic arrays active power is:-

$$P_{PV} + P_{LOS} = P_{Inv}$$

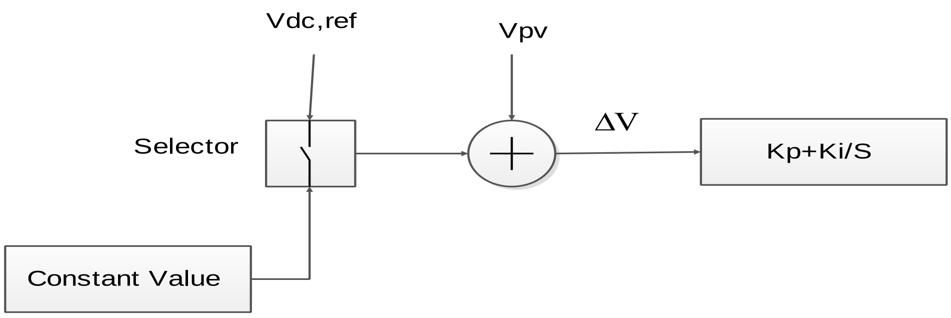

Fig 5.3 Active power control method of inverter

The above Fig 5.3 shows the active power control of the inverter. Here we can see the selector and the constant value which if the irradiance is low will provide voltage to the grid. In the simulation performed a simple MATLAB programming was taken in-stead of this block diagram.

```
function V = fcn(Vdc)
%#codegen
k=240;
if (Vdc > 132.8)
    V=Vdc;
else
    V=k;
end
```

To control the output current of the inverter the hysteresis band technique is used. This technique is used because it would keep the inverter's output current in acertain permissible zone, so that it does not affects other equipment.

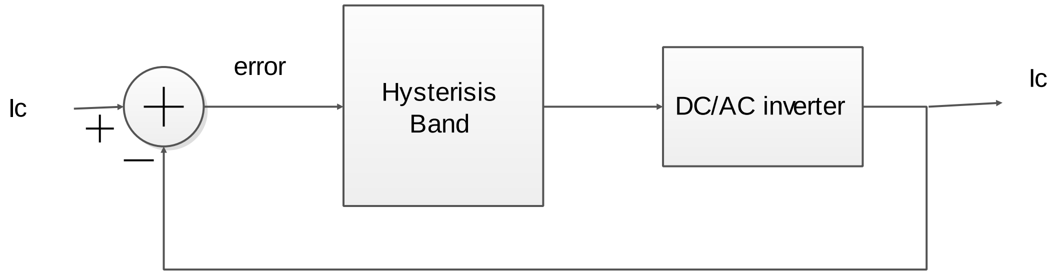

Fig 5.4 Hysteresis band controller

5.2 Stability and power quality issues in PV connected micro-grid without MPPT algorithm and power control methods.

As in Fig. 5.2 it is shown that a PV array is connected to a grid through an inverter. The reason for observing and understanding the power quality issues and stability of PV is that if there is a sudden change in weather and suddenly solar radiation is decreased, then what can be done [2] [9]. As we could not perform this experiment with hardware setup, so we performed it in the MATLAB/Simulink software and for the weather conditions, the irradiation levels were decreased and the temperature was also decreased. The waveforms of both active and reactive powers were simulated and both the waveforms are compared.

5.3 Simulations

All the simulations were carried out in MATLAB/Simulink software. The values of different components taken are shown in the tables below. The simulation diagrams are shown in the next pages as well.

Table 5.1 Values of load and grid

Description	Parameters
Inductive Coupling	L_C = 30.7mH
DC Bus Capacitor	C_{DC} = 1.3mF
Load	R_L = 10Ω, L_L = 20mH, C_L =
Grid	V_S = 230 V
Frequency	f = 50Hz
Induction of Grid	L_S = 0.15mH

Table 5.2 Values of PV array

Description	Parameters
Number of PV arrays in series	30
Number of PV arrays in parallel	6
Open circuit voltage of single PV array	21.75 V
Short circuit current of single PV array	3.45 A
Reference Solar radiation	1000 W/m^2
Reference Temperature	25^o C
Saturation diode current	4.05e-7 A

The above values were taken for the component while performing the simulations using MATLAB/Simulink software. The below simulation diagrams are of different parts of the whole diagram.

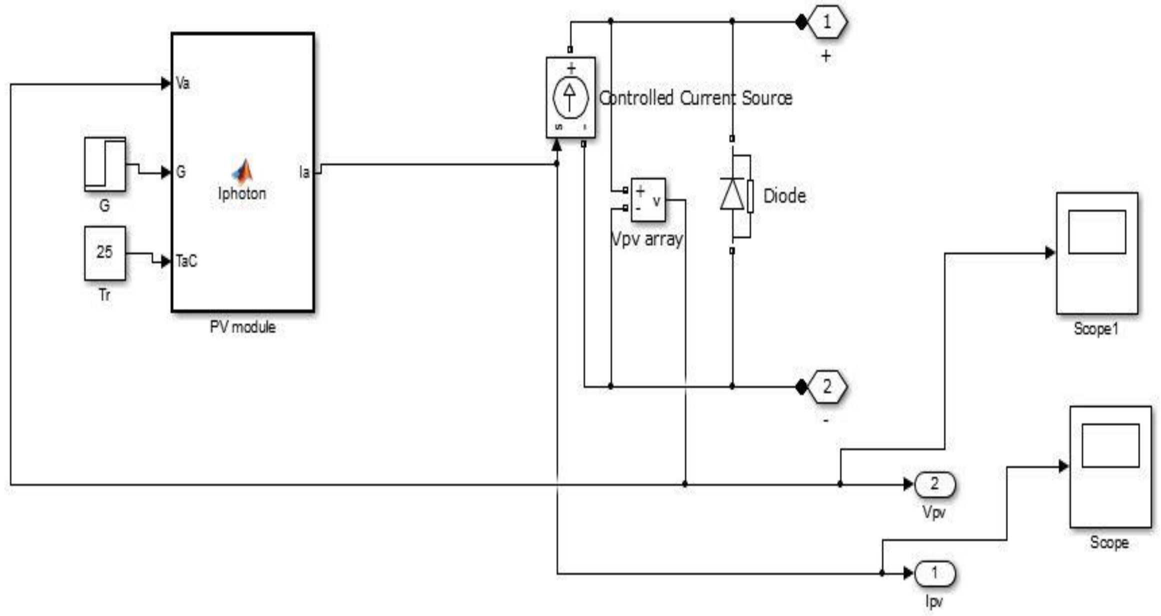

Fig 5.5 PV array

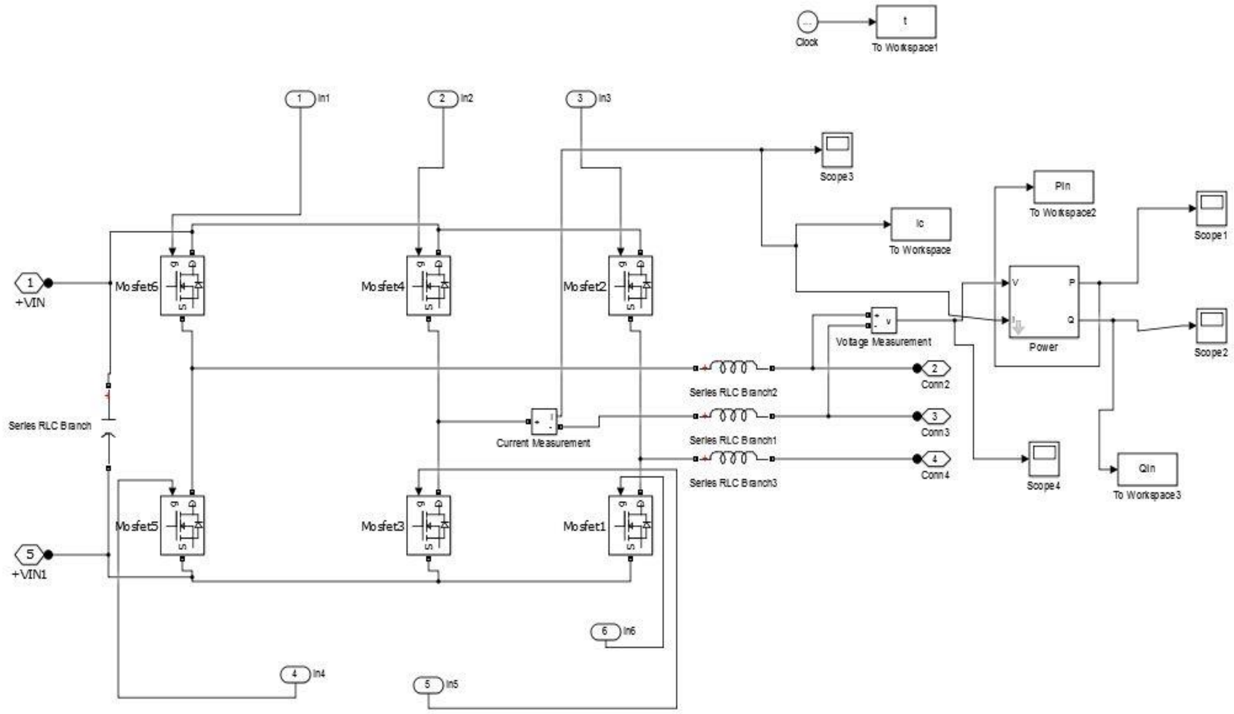

Fig 5.6 Inverter Simulink diagram

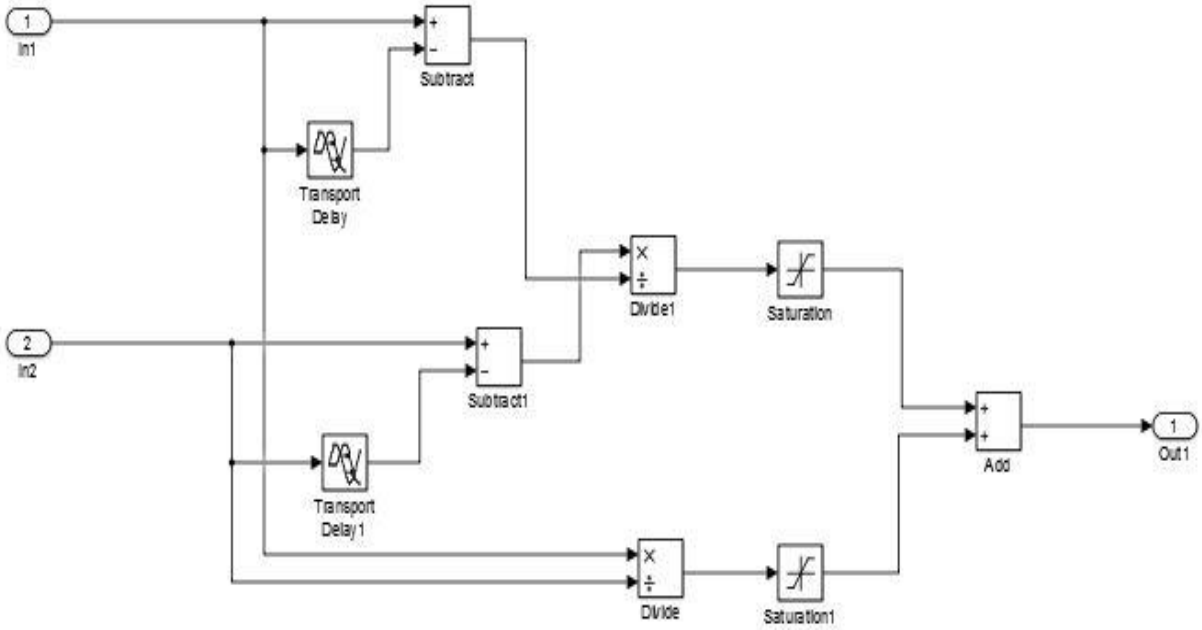

Fig 5.7 IC Simulink diagram

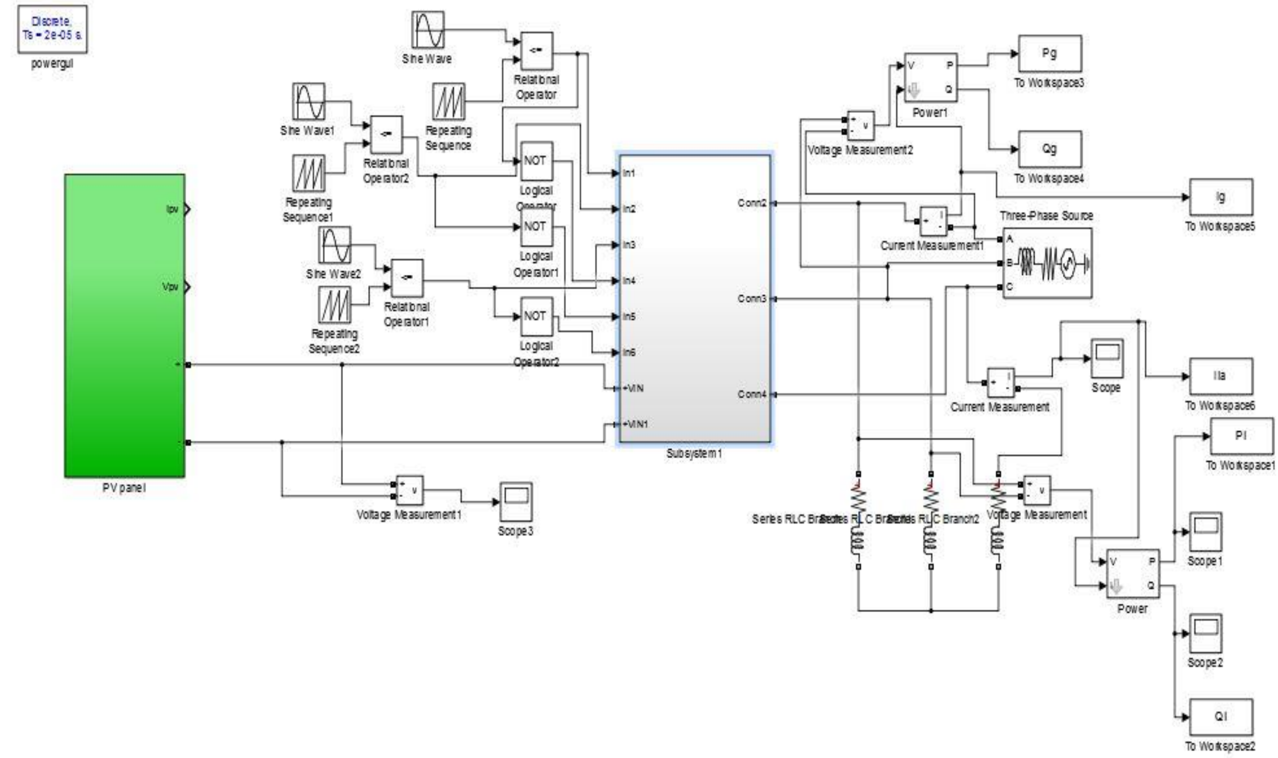

Fig 5.8 PV array without control schemes

Photovoltaic array programming in MATLAB

```
function Ia=Iphoton(Va,G,TaC)
k = 1.381e-23;
q = 1.602e-19;
n = 1.3;
Eg = 1.12;
Ns = 30;
Np=6;
TrK = 299;
Voc_TrK = 21.75 /Ns;
Isc_TrK = 3.45 /Np;
a = 1.33e-3;
TaK = 273 + TaC;
Vc = Va / Ns;

Isc = Isc_TrK * (1 + (a * (TaK - TrK)));

Iph = G * Isc;

Vt_TrK = n * k * TrK / q;

b = Eg * q /(n * k);

Ir_TrK = Isc_TrK / (exp(Voc_TrK / Vt_TrK) -1);
Ir = Ir_TrK * (TaK / TrK)^(3/n) * exp(-b * (1 / TaK -1 / TrK));

dVdI_Voc = -2.0/Ns;
Xv = Ir_TrK / Vt_TrK * exp(Voc_TrK / Vt_TrK);
Rs = - dVdI_Voc - 1/Xv;

Vt_Ta = n * k * TaK / q;

Ia=zeros(size(Vc));
for j=1:5;
   Ia = Ia - (Iph - Ia - Ir .* ( exp((Vc + Ia .* Rs) ./ Vt_Ta) -1))...
       ./ (-1 - Ir * (Rs ./ Vt_Ta) .* exp((Vc + Ia .* Rs) ./ Vt_Ta));
end
Ia=Ia*Np;
end
```

Chapter 6

Results and Discussions

6.1 PV array with MPPT algorithm and power control techniques.

PV Array

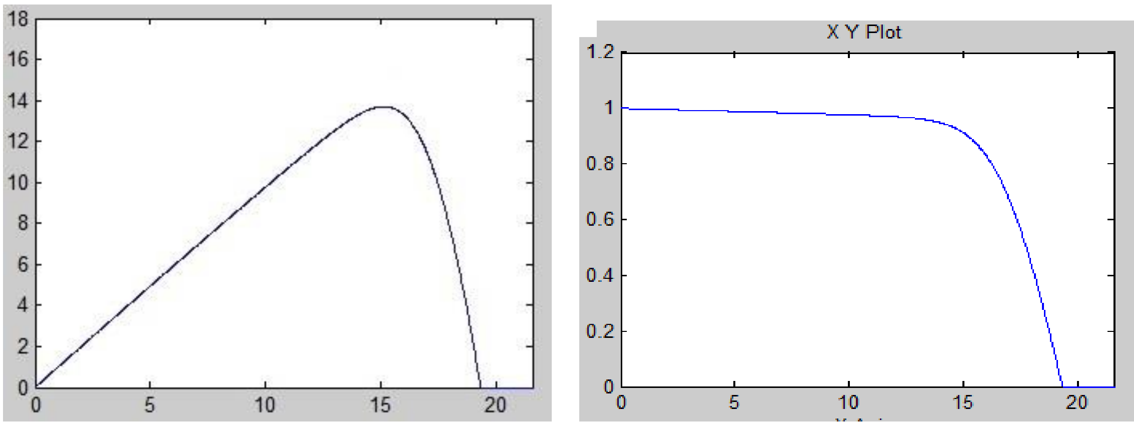

Fig 6.1 PV curve (a) IV curve (b) of PV array

The Fig 6.1 represent the power vs. voltage curve and current vs. voltage curve of the PV array. Here only the curves are drawn for one temperature. If the temperature is increased then the P_{MAX} will also increase with it and as far as operating current is concerned, it will also increase but the operating voltage will decrease as we increase the temperature. As we can see in fig the MPP is reached at the top most point which is then transferred further in the circuit.

RL load

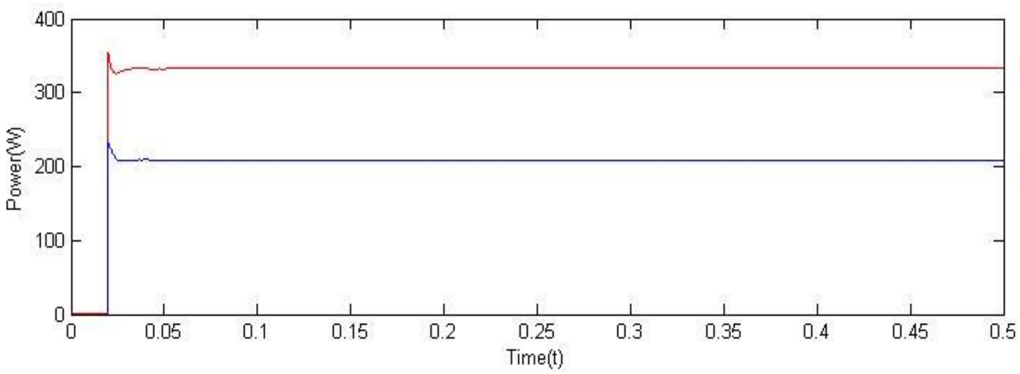

Fig 6.2 Active and reactive power of load (RL)

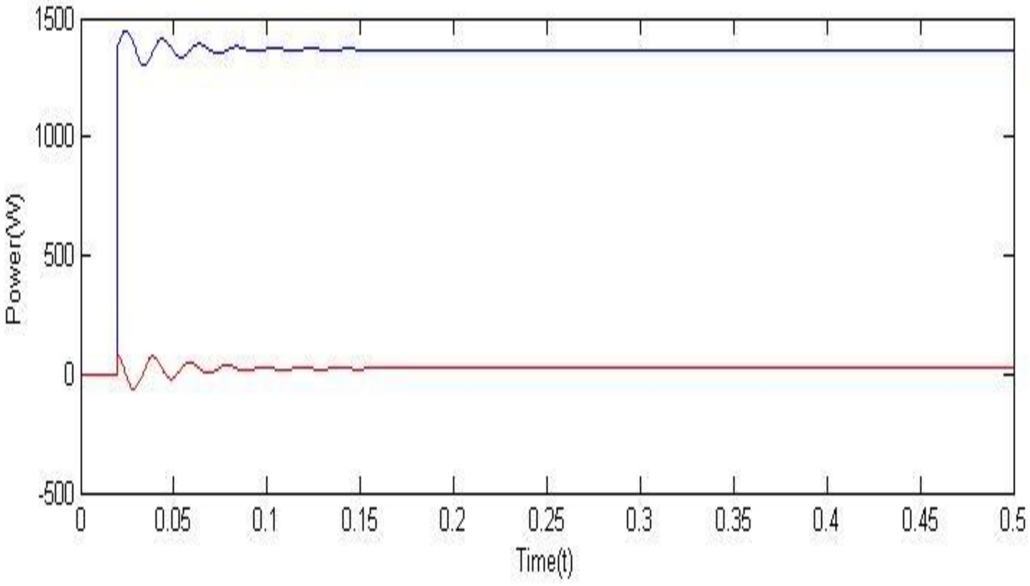

Fig 6.3 Active and reactive power of grid (RL)

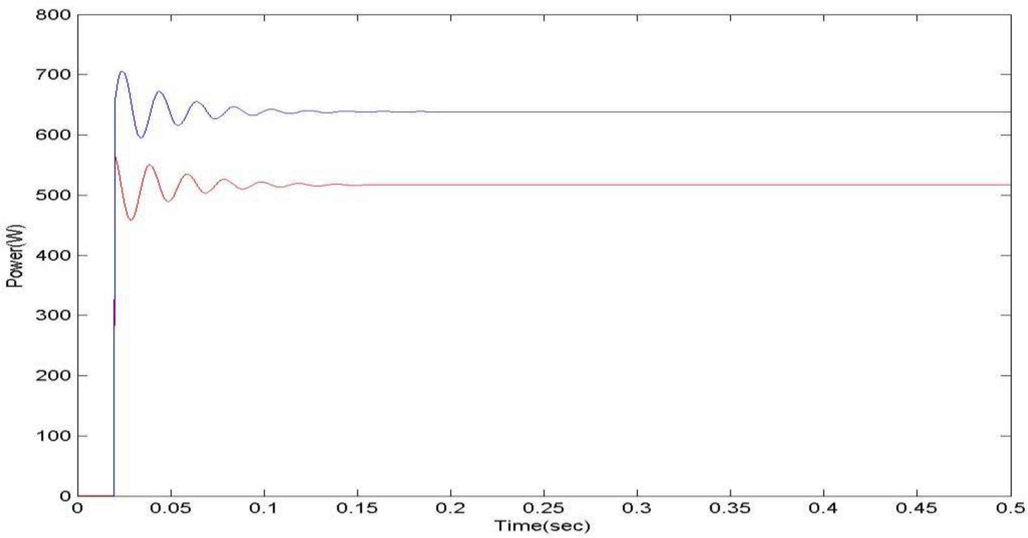

Fig 6.4 Active and reactive power of inverter (RL)

The above waveforms show the power of the load, grid and inverter respectively. As we can see due to the usage of MPPT algorithm and the proposed control scheme for active and reactive power, the active and reactive power of load are quite similar (Fig 6.2). As a matter of fact they are having a very good power factor. This improves the power quality, which is being supplied to the consumers and is good for power quality analysis.

The Fig 6.3 shows that the reactive power is greater than the active power. It only means the grid is supplying power to the load rather than storing power. As the grid provides more power to the load, the PV array can be used to assist the main grid in supplying power to the consumers. The Fig 6.4 shows the inverter's active and reactive powers. It shows that they both tend to have a unity power factor, which is helpful in achieving better power quality.

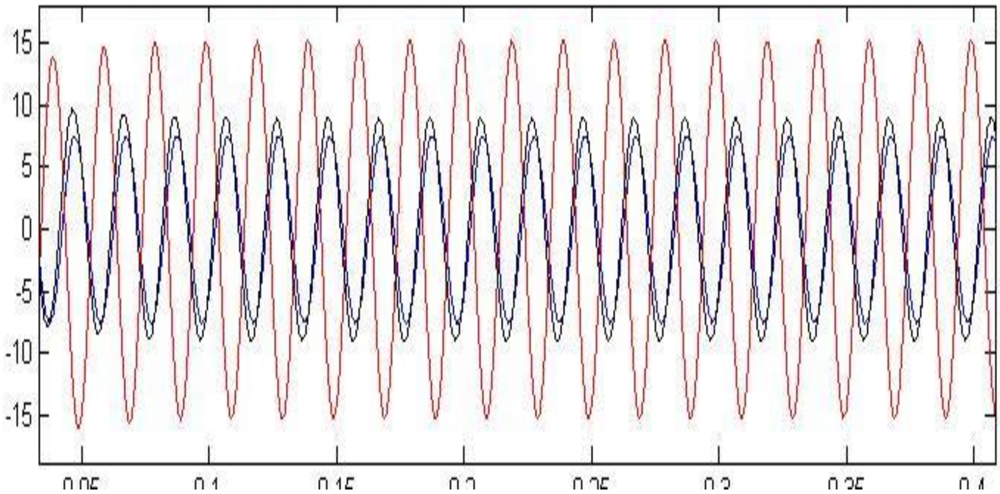

Fig 6.5 Current waveforms (RL)

I_{la} = Load Current (Red)

I_g = Grid Current (Blue)

I_c = Inductor Current (Black)

The current waveforms are simulated as shown (Fig 6.5). The sum of the grid current, I_g and inductor current, I_c is equal to the load current, I_{la} as the waveforms show. The currents taken here are the phase currents only.

$$I_{la} = I_g + I_c$$

L load

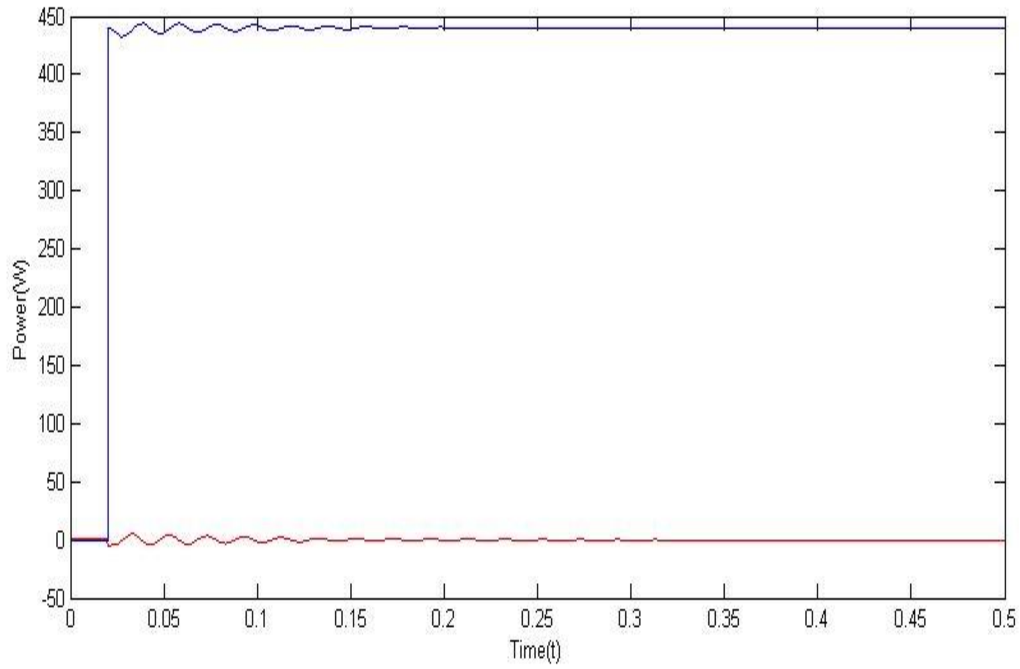

Fig 6.6 Active and reactive power of load (L)

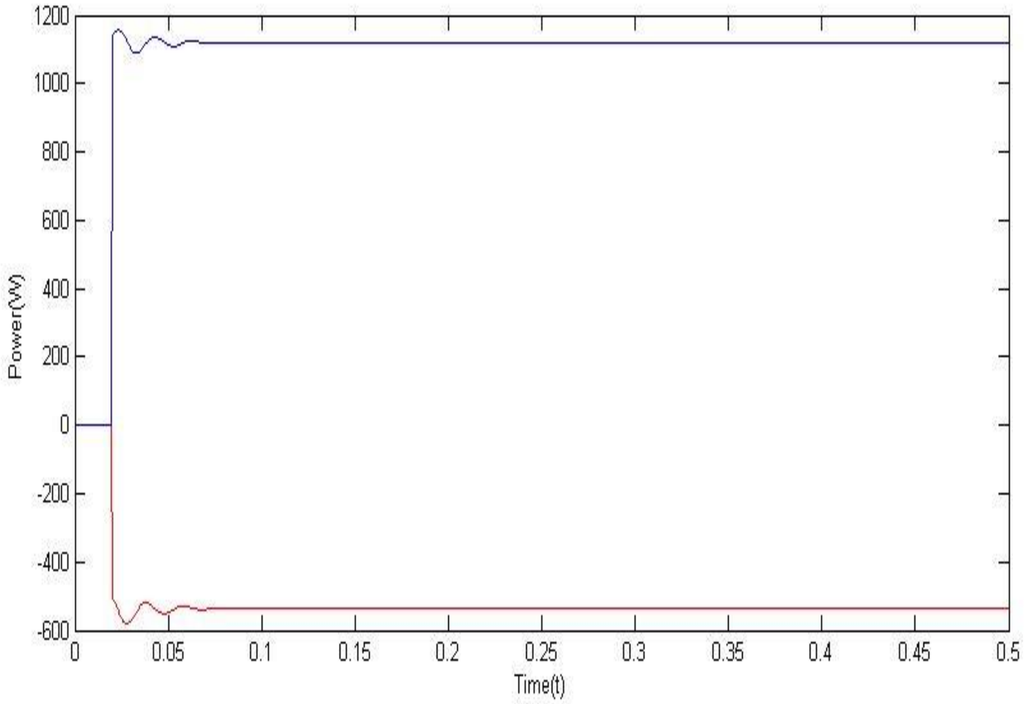

Fig 6.7 Active and reactive power of grid (L)

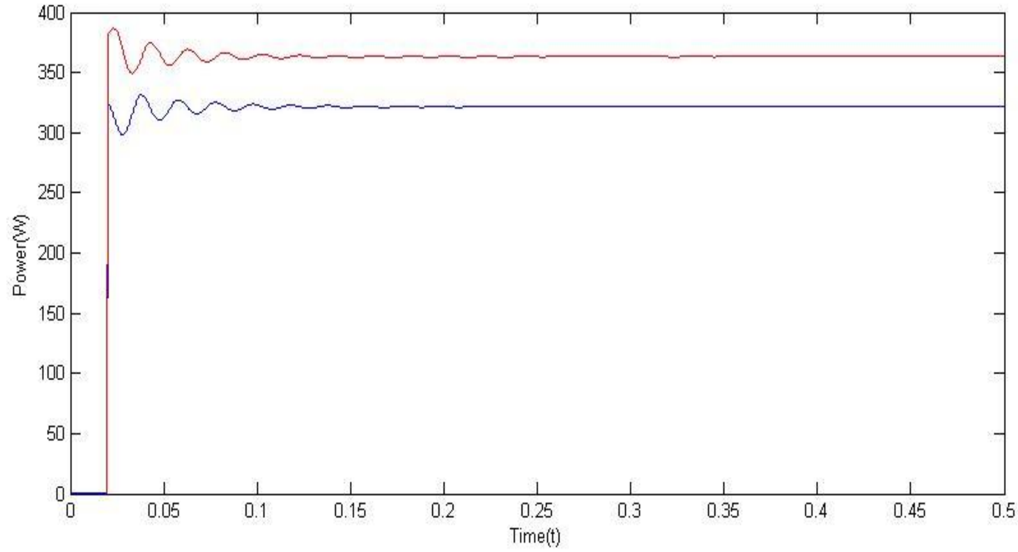

Fig 6.8 Active and reactive power of (L)

As we can see in Fig 6.6 the reactive power is around 420W and active power is zero, which means the inductor is absorbing most of the power. The load is supplying power to the circuit. The grid in Fig 6.7 is having a reactive power of 1.1KW which means the power is being supplied by the grid to the load, as the inductor is absorbing the power.

The inductor's power flow remains unchanged. The active and reactive powers hold the same limit. (Fig 6.8)

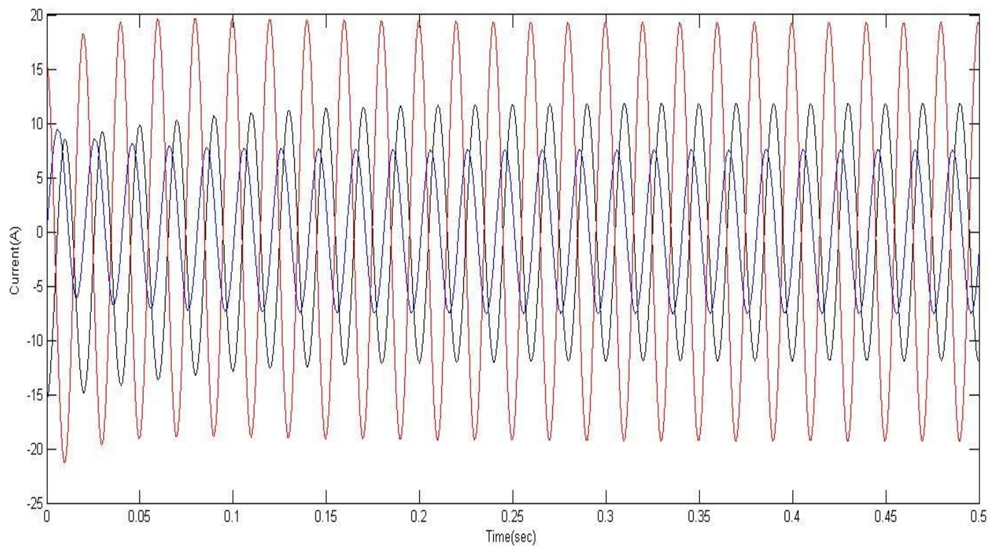

Fig 6.9 Currents waveforms (L)

As in the above Fig 6.9 we see that the load current ($I_{la)}$ is increased to 20A. this might happen due to the power supply from both grid and PV array. The grid current (I_g) has also increased to 10A but the inductor current (I_c) remains unchanged.

R load

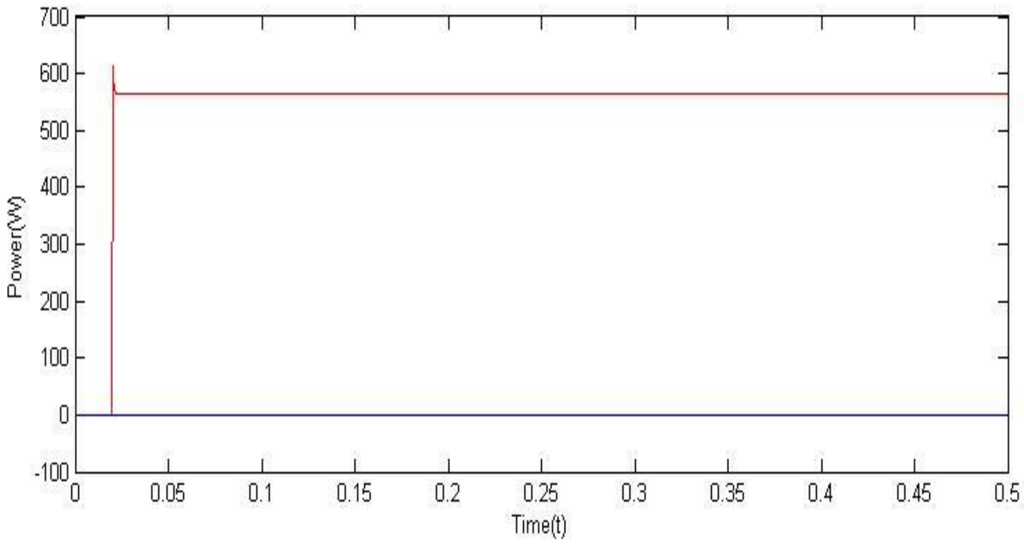

Fig 6.10 Active and reactive power of load (R)

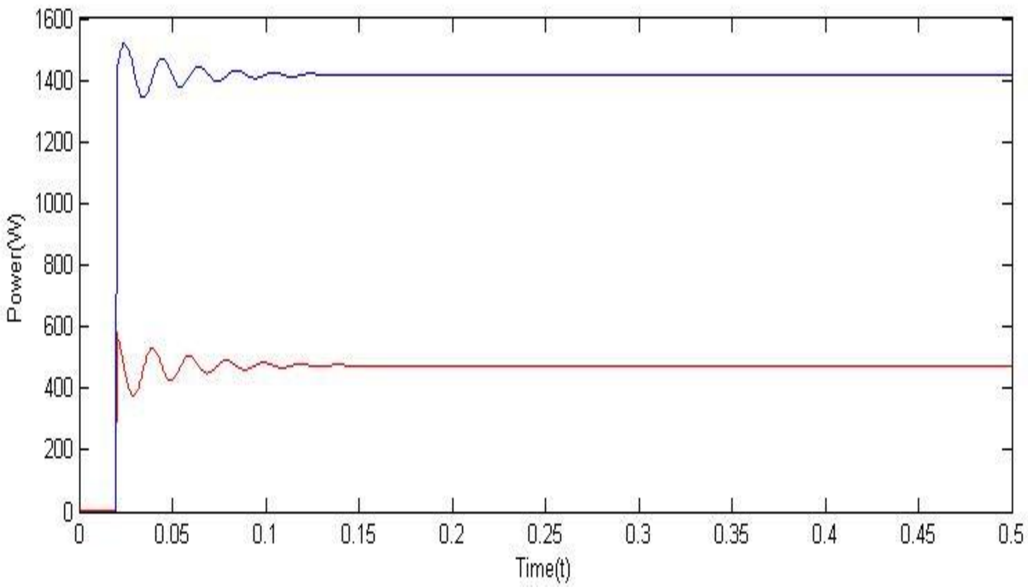

Fig 6.11 Active and reactive power of grid (R)

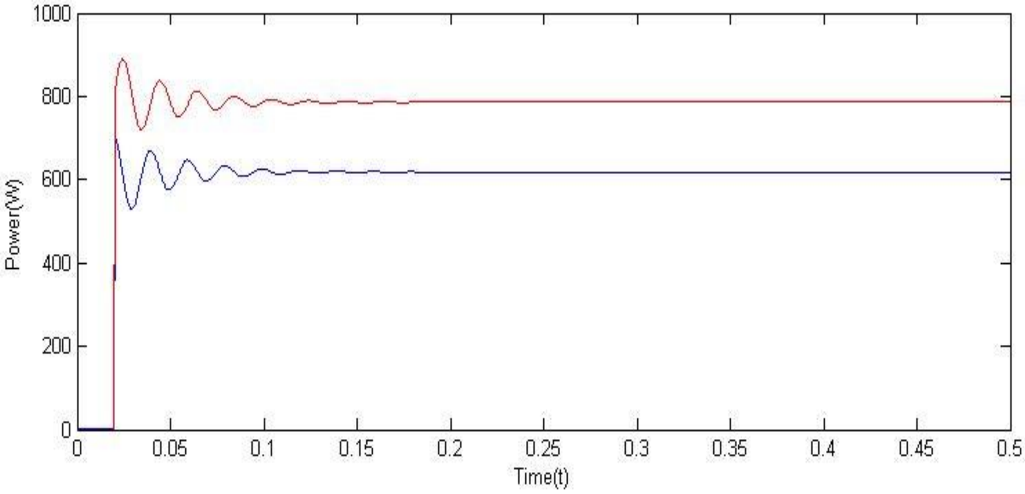

Fig 6.12 Active and reactive power of inverter (R)

The above figures show the power of load, grid and inverter when the load is only resistive. We see in Fig 6.10 that the active power is 550W while reactive power is zero. This suggests that using resistive load the power factor is very good and the useful power is only available. In Fig 6.11 the reactive power is pf the value of 1.4KW which suggests that the grid is supplying power to the load as well. The active power flowing through the grid is very low considering the reactive power. The active and reactive powers through inverter remain unchanged. (Fig 6.12)

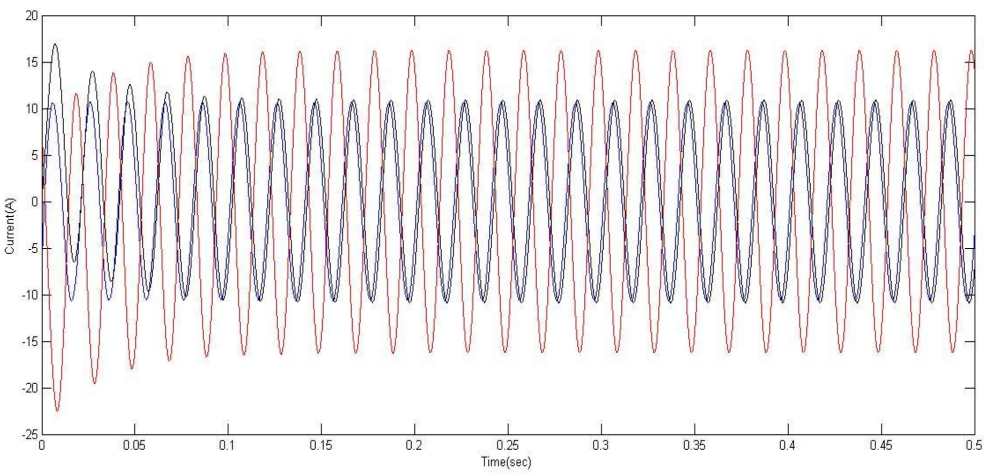

Fig 6.13 Current waveforms (R)

The load current has a value of 15A and is sinusoidal, whereas both grid and inductor current are of 8A each (Fig 6.13). This proves the formula:-

$$I_{la} = I_g + I_c$$

RLC load

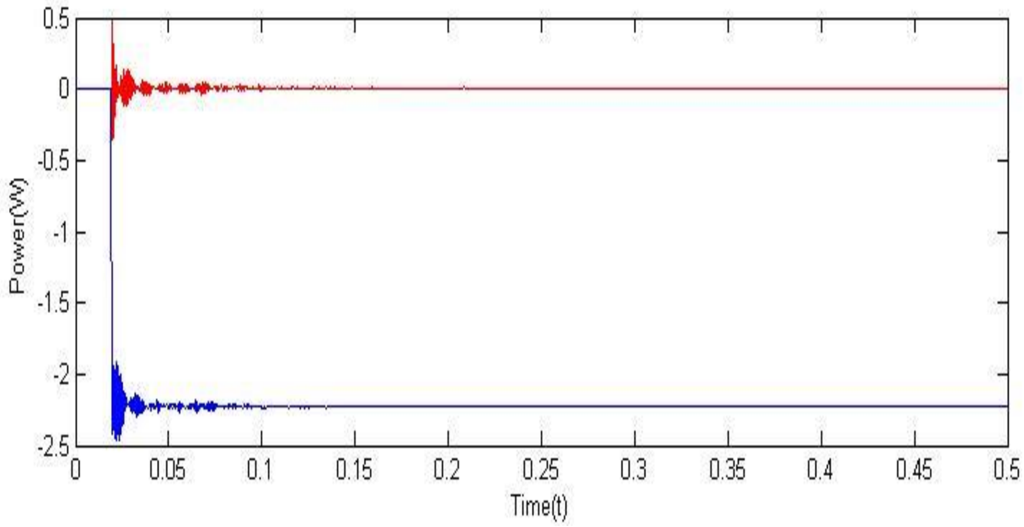

Fig 6.14 Active and reactive power of load (RLC)

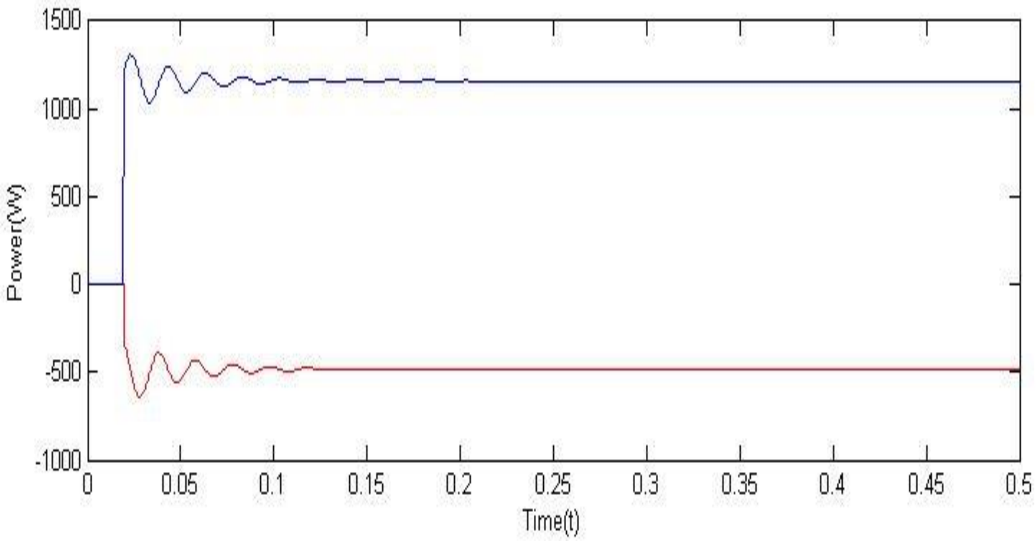

Fig 6.15 Active and reactive power of grid (RLC)

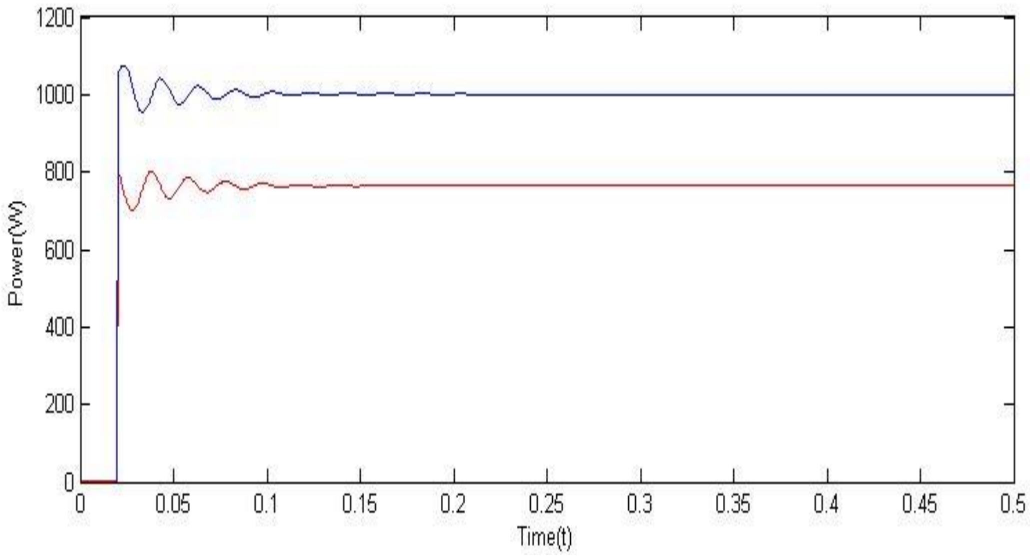

Fig 6.16 Active and reactive power of inverter (RLC)

The above waveforms shows the power when a RLC load is connected. As we can see in Fig 6.14 the active power is zero and reactive power has a negative value. This is because the capacitor supplies power to the load and the inductor absorbs most of the power. The grid in a RLC load supplies power to the circuit and its reactive power is also high (fig 6.15). The inductor power levels remain unchanged. (Fig 6.16)

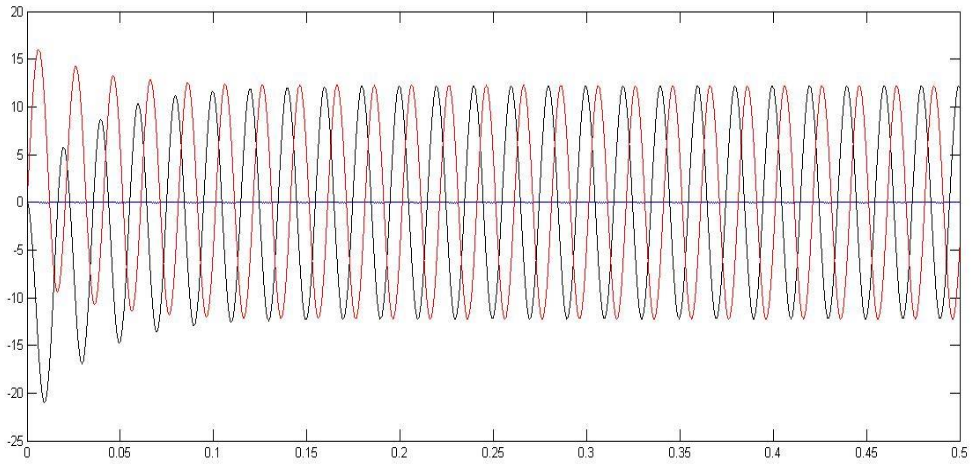

Fig 6.17 Current waveforms (RLC)

The above Fig 6.17 shows the currents during an RLC load connection. It is observed that the load and grid current are of similar value i.e 10A but there is no current flowing through the inductor. This means all the current from the grid is being fed to the load.

6.2 PV array connected to grid without any MPPT algorithm and control scheme.

RL load

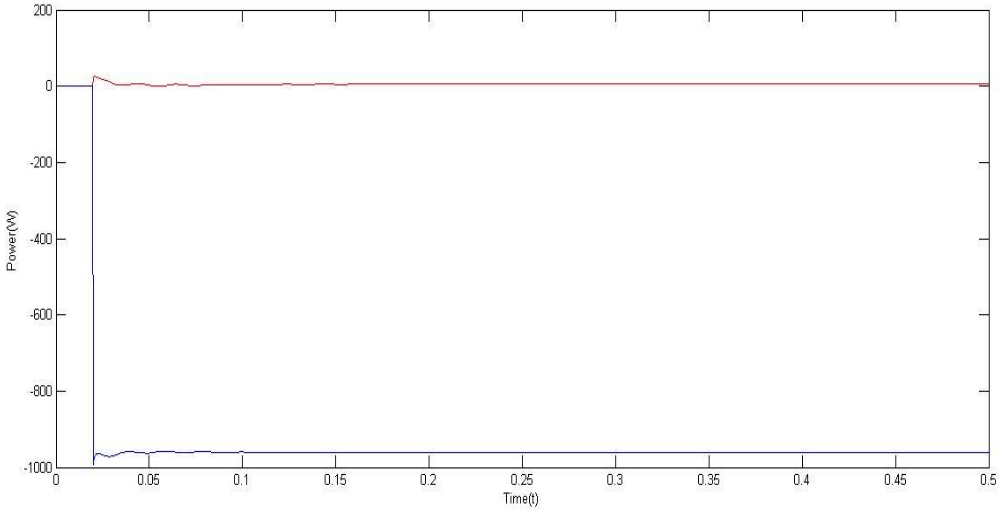

Fig 6.18 Active and reactive power of load (RL)

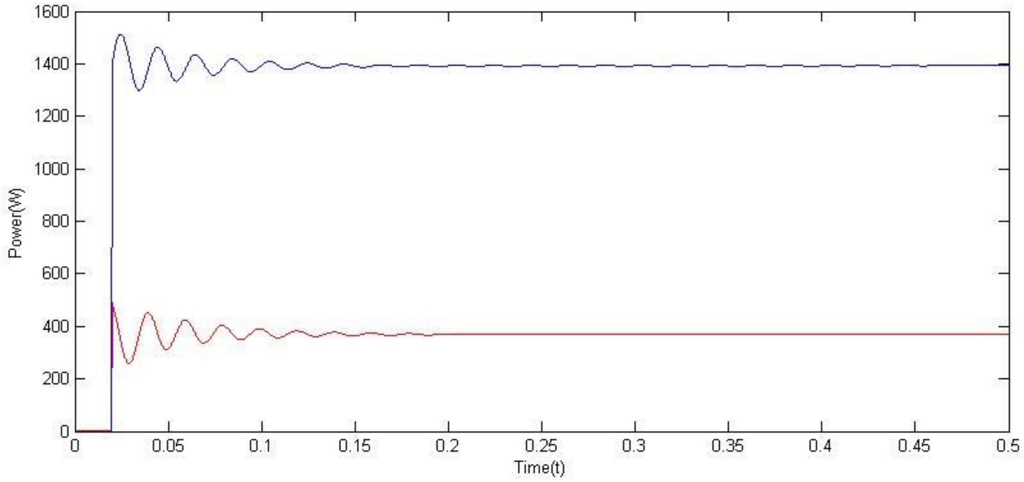

Fig 6.19 Active and reactive power of grid (RL)

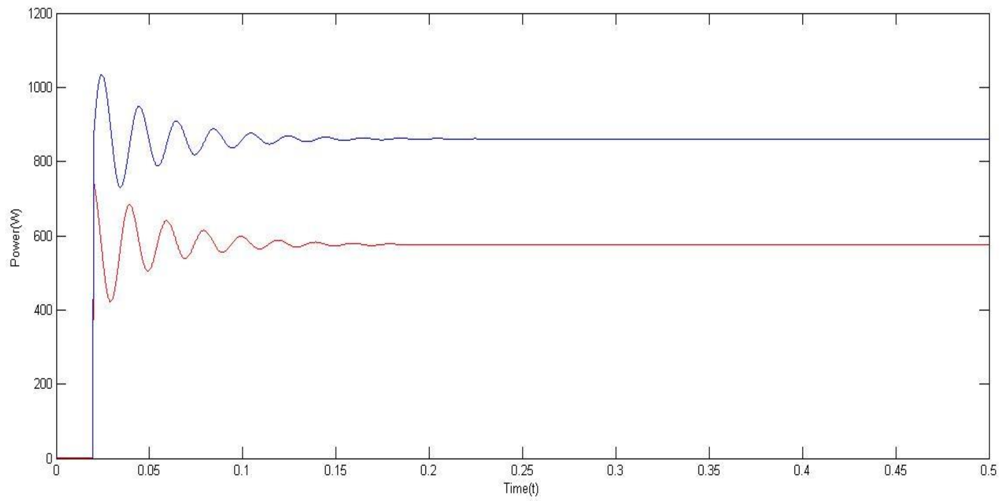

Fig 6.20 Active and reactive power of inverter (RLC)

The above waveforms show the power levels of a grid connected PV without any control schemes. The load's active power seems to be very low and it in return provides the circuit with (Fig 6.18). The negative polarity of the reactive power suggest power flow is in opposite directions. The grid has reactive power of the value 1.5KW which is very much high and the power factor is not healthy for better power supply (fig 6.19). The losses in these circuits is high, as the useful power is very much less. The inverter's active and reactive power remains similar to the previous attained values. (Fig 6.20)

L load

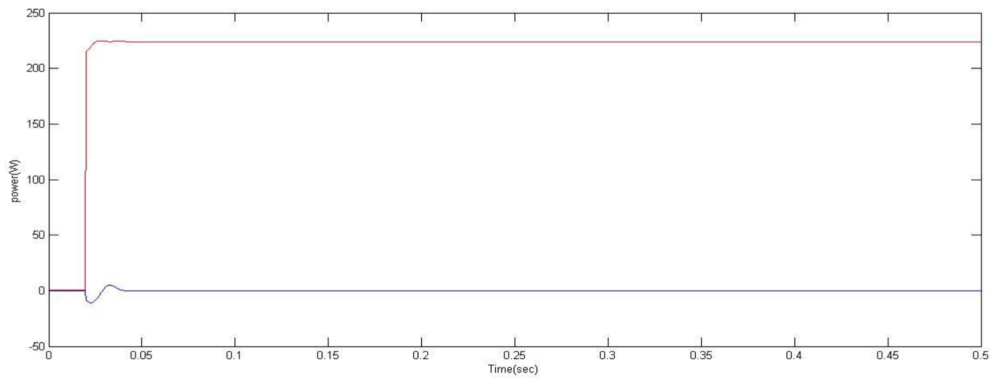

Fig 6.21 Active and reactive power of load (L)

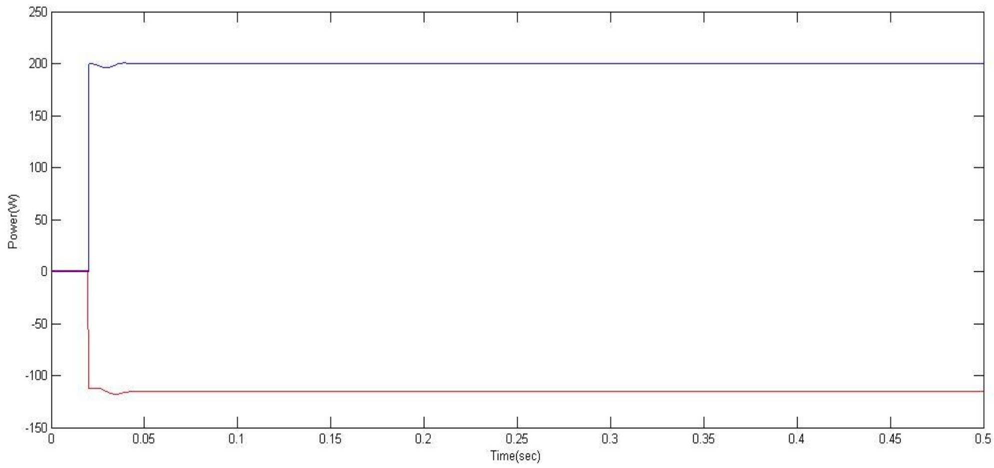

Fig 6.22 Active and reactive power of grid (L)

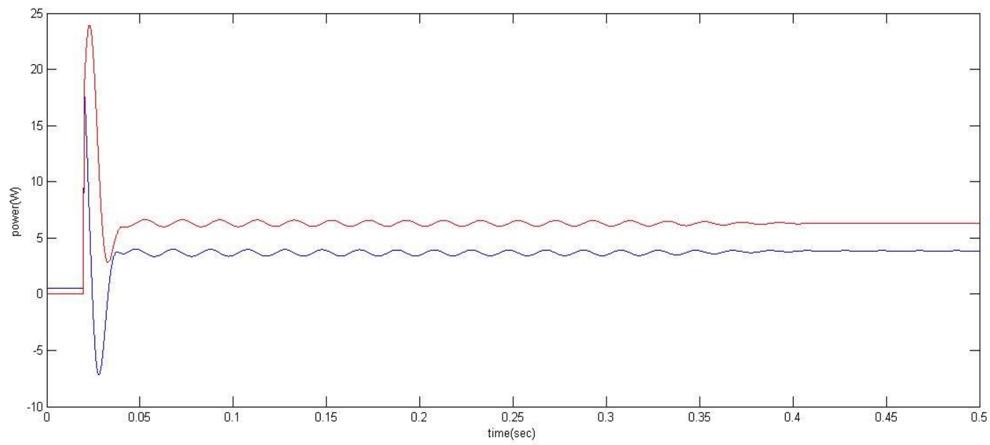

Fig 6.23 Active and reactive power of inverter (L)

The above waveform show the power of load, grid and inverter if only an inductive load is attached to the PV array and grid. The load shows that the active power is around 200W with the reactive power being nearly zero (Fig 6.21). This is explained as the inductive load tends to absorb power from the array and grid both. The grid supplies active power to the circuit, bur the reactive power is way above the limit (Fig 6.22). In the inductor the active and reactive power remain at a constant value showing that the power through the inverter is properly flowing to the load. (Fig 6.23)

R load

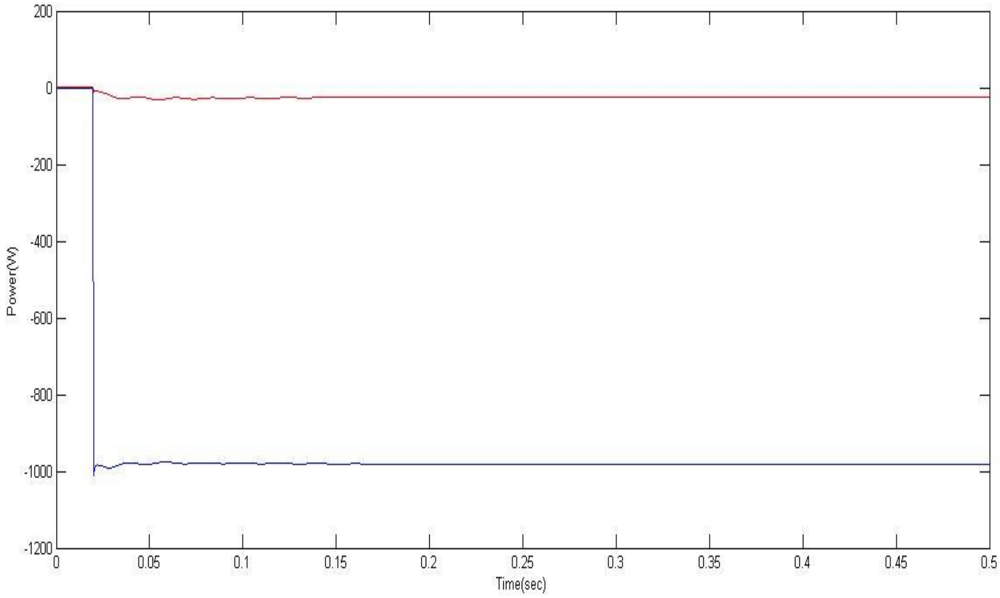

Fig 6.24 Active and reactive power of load (R)

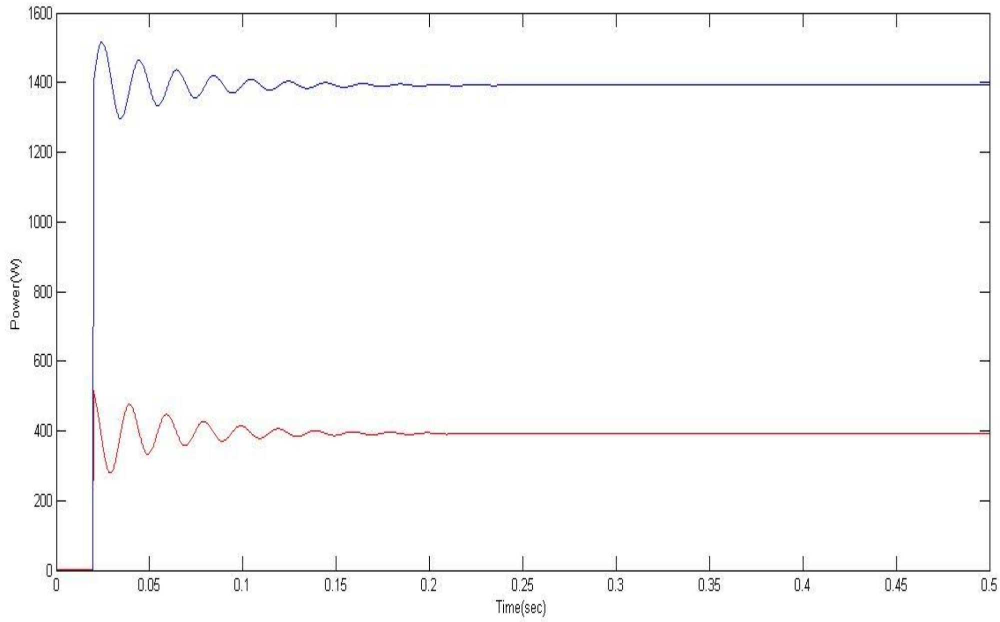

Fig 6.25 Active and reactive power of grid (R)

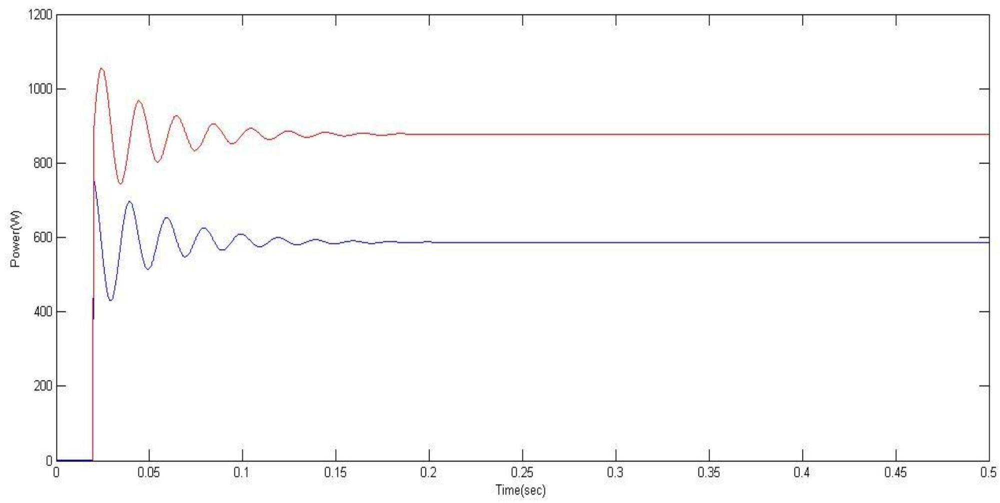

Fig 6.26 Active and reactive power of inverter (R)

The fig 6.24 shows that the active power in the load circuit is almost zero but the reactive power is negative. This means that the load supplies reactive power to the circuit. As the levels of active power is very low, it is not suitable for usage. The grid absorbs and stores much of the reactive power provided by the load and in return it provides active power to the inverter, not to the load (Fig 6.25). The active and reactive power in the inverter remain similar to the values as when the control schemes were applied. (Fig 6.26)

RLC load

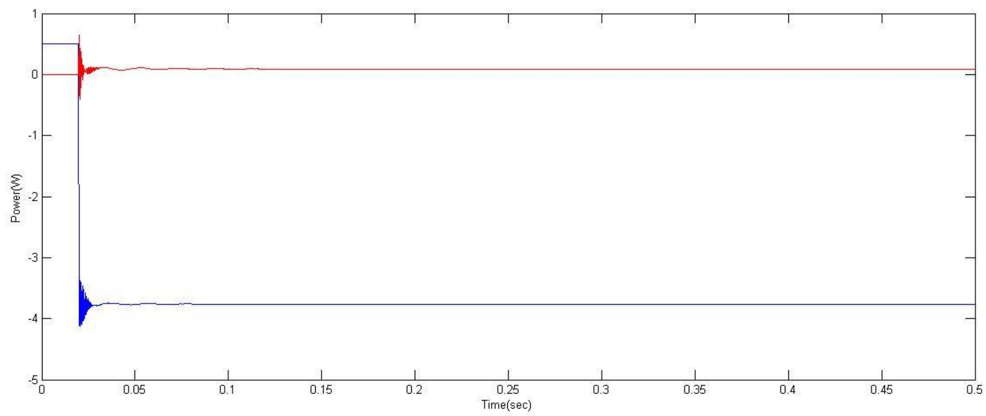

Fig 6.27 Active and reactive power of load (RLC)

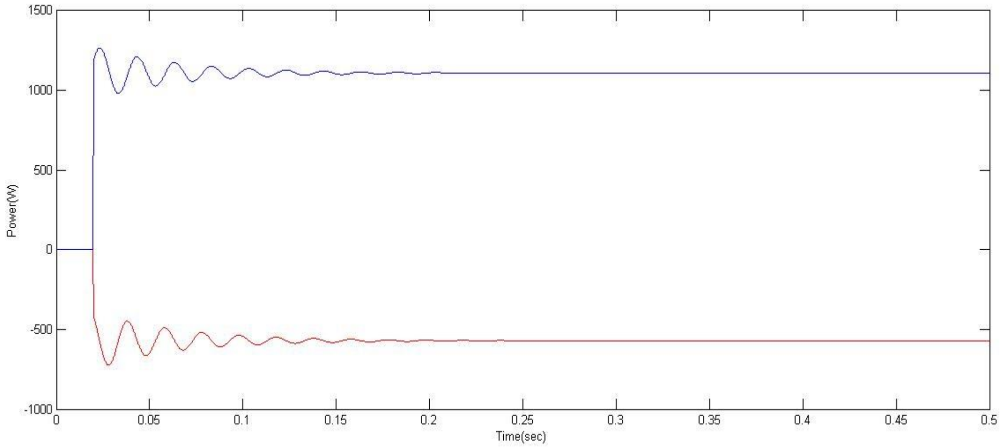

Fig 6.28 Active and reactive power of grid (RLC)

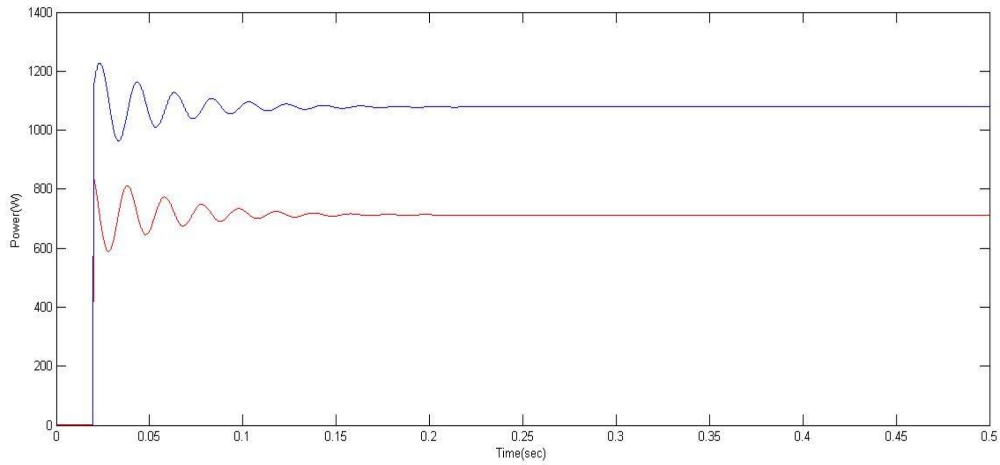

Fig 6. 29 Active and reactive power of inverter (RLC)

The Fig 6.27 shows that the load now supplies power to the circuit, both active and reactive power. Both of them are of meagre value and have negative polarity. The grid (Fig 6.28) provides active power to the inverter and absorbs the reactive power of both load and inverter. The inverter has the active and reactive power at similar values as before. (Fig 6.29)

6.3 Conclusion and future work

We see from the simulations performed and the output produced, when the grid connected PV array has an MPPT algorithm to search the MPP and a control scheme for both active and reactive power, the power factor has a good value and the reliability of the power supply remains good. While if we use PV array without any of the control methods, then the reactive power increases and much power is being drawn from the load. This way the PV array is not very useful to the consumers.

The future work in the above simulations can be done by performing the real time experiments of the simulations. In real time we will know about the righteousness of the results obtained from Simulink.

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